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IGLC 31
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INTERNATIONAL GROUP FOR LEAN CONSTRUCTION

INSTITUT FRANÇAIS DE LA CONSTRUCTION LEAN

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Proceedings of the 31th Annual Conference of the International Group for Lean Construction

Where architecture, engineering, and construction get lean, in principle and in practice

Editors:
Dr. Zofia Rybkowski, Dr. Min Liu, and Dr. Saad Sarhan

Proceedings of the 31st Annual Conference of the International Group for Lean Construction (IGLC31)

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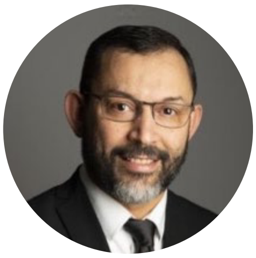

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A MESSAGE FROM THE CONFERENCE CHAIR

Welcome to the *31st International Group for Lean Construction Conference (IGLC31)* in Lille, France

Dear Participants attending the 31st International Group for Lean Construction (IGLC31) Conference in Lille (France),

As Chair of the Organizing Committee of (IGLC31) Conference, it is my pleasure to welcome you to this pivotal event. We stand at the cusp of extraordinary transformation within the construction industry, and this conference is a platform for progressive minds to convene, address critical issues, and seek innovative solutions.

The construction sector, a longstanding symbol of human creativity shaping our societies, is in flux. We're amidst a paradigm shift spurred by globalization, digitization, urbanization, and increased sustainability needs. Our focus is on streamlining resources and enhancing quality and work conditions. Given construction's significant contribution to global CO_2 emissions, we must create structures that are resilient, aesthetically pleasing, and eco-friendly. The future belongs to green buildings, low-carbon materials, and high-efficiency technologies.

The rapid adoption of technologies such as artificial intelligence and Building Information Modelling (BIM) brings opportunities and challenges alike. As we employ these innovations, we must ensure our workforce can keep up with this tech revolution. That's where Lean Construction is crucial—no tech transformation can occur without a comprehensively understood Lean approach and social relations.

Rapid urbanization heaps immense pressure on our infrastructure. Our duty is to create inclusive, intelligent, and sustainable cities meeting everyone's needs. Amid these shifts, we must not lose sight of the human element—our construction workers' safety, health, and well-being. Although these challenges are profound, they present opportunities to rethink, reimagine, and reinvent. Our sector thrives on challenges; it's this determination that will shape a sustainable, fair, and innovative future.

The number of contributions this year is exceptional, with numerous topics of great interest to the construction community. I want to take this opportunity to express my gratitude to the external reviewers of the full papers. The organization of this event would not reach the necessary high scientific and technological standards without the skilled work of these reviewers. I would like to extend my warmest thanks to the IGLC31 scientific committee, in particular Zofia Rybkowski, Texas A&M University and the entire committee, who did an outstanding job of steering the conference. I would like to thank the Centrale Lille Institut and the IFCL for their ongoing support in making IGLC31 a great success.

IGLC31 is more than a conference; it is a global assembly of over 250 researchers and practitioners, from all over the world. This program embodies our collective vision of the future of construction. As you read through its pages, you will find articles to bring you ideas that will inspire, knowledge that will empower, and connections that will endure.

We are gathered here to build the future, and there is no task more noble or more necessary. Let's learn, share, collaborate, and transform our industry for the better.

Together, let's build a better future.

Warm Regards,

Prof. Dr. Zoubeir LAFHAJ
Full Professor
Centrale Lille Institut
Chair Holder in Construction 4.0
Founder and President of IFCL (French Institute of Lean Construction)
President of the 31st Annual Conference of the International Group of Lean Construction (IGLC)

FROM THE DESK OF THE SCIENTIFIC CHAIR

Dear Attendee:

Welcome to the *31st International Group for Lean Construction Conference* in Lille, France!

I cannot think of a more exciting place to share this week together with you, my colleagues of the Lean Construction community.

I am guessing your Lean journey is much like my own. I was introduced to the great pioneers of Lean Construction nearly twenty years ago when I embarked on my doctoral research at the University of California at Berkeley in the fall of 2004. Having practiced in the US and overseas as a young architectural designer before returning to academia, I intuitively knew that existing project delivery practices were deeply flawed. For example, why did my colleagues and I find ourselves working late into the night on project details that had already been revised and were now obsolete, while clients were being billed for our irrelevant hours spent? Why weren't we included in meetings so we could contribute in a meaningful way and grow our knowledge base? Like so many of you, I found these practices demoralizing and believed there was a better way to deliver projects. It was simple common sense that is ironically so *un*common (as the late Greg Howell used to say) that drew me toward Lean Construction and its culture of respect.

Since then, I've attended multiple IGLC conferences across the globe: Manchester, Haifa, Lima, San Diego, Fortaleza, Oslo, Boston, Chennai, Dublin, Edmonton—and even Berkeley and Lima (again) as our hosts carried us valiantly through COVID using an online format.

I am grateful for the *international* embrace of the IGLC. Unlike many other annual, mega-conferences that can sometimes seem nearly indistinguishable year-to-year, every IGLC gathering is uniquely defined by its cultural setting, its hosts, and its active participants. When I think about Lean, I think about *inclusivity*. Lean construction principles are informed by the wisdom of multiple disciplines: engineering and project management, to be sure, but also philosophy, psychology, and architecture. The week of a typical IGLC conference includes both academics *and* practitioners. The longer I serve as a former-practitioner-turned-academic, the more amazed I am about how rare the culture of Lean Construction is.

Lean is sometimes described as an inverted pyramid, where project planners are responsible for supporting the efforts and lightening the load of those who do the heavy lifting. Lean leaders are charged to listen well to those with their boots on the ground. One of my favorite sayings was introduced to me by Alan Mossman: "With every pair of hands comes a free brain." In Lean, we live and breathe within a culture of respect. Although not always perfect, the striving to respect is ennobling. It is also, unfortunately, surprisingly rare.

Academic researchers typically report on the number of papers we've published in conference proceedings and journals. So much of academic research requires "checking the boxes," regardless of how read or impactful our research actually is. Lean Construction academics need to check-the-boxes too (universities require it), but our mission above all is to solve the project delivery problem by first identifying and addressing its root causes, working in partnership with members of industry, and then transferring solutions to real projects using action research. Lean academics and practitioners are united by something greater than ourselves, and it is for this spirit that I am incredibly grateful.

Whether this is your first IGLC conference or one of many, I know this week will serve as a unique maker of memories. This is the first *fully* in-person conference held since the coronavirus disrupted our world and challenged our sense of normalcy. Remote conferencing serves a purpose, but as Rafael Sacks once remarked, it is hard to imagine that the Lean Construction community could have coalesced and had the global impact it has had during the past three decades using only online platforms and videos.

Please be sure you take part in as much of the week as you can: Workshop Day, Industry Day, and the Technical Conference, whether at this year's IGLC or next. Don't miss one of my favorite events of all—**the simulation gaming session** on Thursday afternoon that was started by Iris Tommelein four years ago during our first fully on-line IGLC.

Finally, I'd like to send a big shout out to all those who stepped up to the plate to collectively volunteer thousands of hours, delivering the technical segment of this conference. I thank my scientific committee co-chairs: **Min Liu**, of Syracuse University, **Saad Sarhan** of the University of Lincoln, our coordinator **Wassim Al Balkhy** of the Centrale Lille Institut, and **Cynthia Tsao** of NaviLean who stepped in to help in multiple ways. I am extremely grateful to **Thais Alves** from San Diego State University and **Ken Walsh** from George Mason University who used their over 40 years of collective experience in Lean Construction to select papers for plenary presentations that they felt were of greatest interest to the broadest of audiences, crossing multiple tracks. Thank you, too, to **Suryeon Kim** from Texas A&M University and **Chuanni He** from Syracuse University for so diligently shepherding these proceedings.

I especially thank the **chairs of our twelve tracks** and the **216 reviewers** from around the world who volunteered for the substantial task of ensuring that conference papers met the quality standards required by the IGLC. Their names are listed in the proceedings. If you were an author who submitted a paper and have a chance to meet your track chair either in Lille or elsewhere, please reach out to thank them for their efforts in helping to improve the quality of our papers.

Finally, a big "merci" goes out to **Zoubeir Lafhaj** from the Centrale Lille Institute and his enthusiastic organizational team for hosting the IGLC31 and meeting with the Scientific Committee on a regular basis, ensuring we were aligned in our efforts to create a week of exciting presentations and meaningful discussions. I know these conversations will impact our industry in positive ways during the years to come, as the IGLC already has during the past three decades.

--

Zofia Rybkowski, PhD
Presidential Impact Fellow
Holder of the Endowed Harold Adams Interdisciplinary Professorship
Associate Professor | Department of Construction Science
College of Architecture | Texas A&M University
Chair, Scientific Committee
IGLC31, Lille France

FOREWORD

A total of 172 papers were received, and following a double-blind review, 151 papers were accepted for publication. The accepted papers were organized into twelve tracks: BIM and Enabling Lean with Innovative Technology; Contract and Cost Management; Health, Safety and Quality; Lean and Green; Lean Theory; Learning and Teaching Lean; Modular and Off-site Construction; People, Culture and Change; Product Development, Value and Design Management; Production Planning and Control; Production System Design; and Supply Chain Management. A summary of the submitted and accepted papers by track is shown in Table 1.

Table 1: Papers Accepted to IGLC31 by Theme

Theme	Received	Accepted
BIM and Enabling Lean with Innovative Technology	25	24
Contract and Cost Management	9	8
Health, Safety and Quality	10	7
Lean and Green	11	11
Lean Theory	9	6
Learning and Teaching Lean	7	7
Modular and Off-Site Construction	14	14
People, Culture and Change	16	13
Product Development, Value and Design Management	13	8
Production Planning and Control	33	29
Production System Design	14	14
Supply Chain Management	11	10
Total	**172**	**151**

The accepted papers (Table 2) represent twenty-eight countries including (in alphabetical order, per the first author's affiliation): Australia, Brazil, Canada, Chile, China, Colombia, Denmark, Finland, France, Germany, India, Indonesia, Ireland, Israel, Italy, Japan, Lebanon, Luxembourg, New Zealand, Nigeria, Norway, Peru, Portugal, Qatar, South Africa, Switzerland, United Kingdom, and the United States.

Table 2: Papers Accepted to IGLC31 by Country of First Author's Institution

Countries	Papers Accepted	Countries	Papers Accepted
USA	17	Ireland	4
Canada	17	Japan	3
Brazil	13	Peru	3
Norway	11	New Zealand	3
UK	10	Nigeria	2
Germany	9	Lebanon	2
Finland	8	Colombia	2
Chile	8	Luxembourg	2
France	6	Portugal	2
Australia	5	Italy	2
South Africa	4	Indonesia	1
India	5	Qatar	1
Israel	5	China	1
Denmark	4	Switzerland	1
	Total	**151**	

The high quality of the submissions led us to choose 12 plenary papers worthy of presentation to the entire IGLC audience. The plenary papers are listed in Table 3.

Table 3: Selected Plenary Papers of IGLC31

Plenary paper title	**Presenter**
Using Low-code and Artificial Intelligence to Support Continuous Improvement in the Construction Industry	Eder Martinez University of Applied Sciences and Arts Northwestern Switzerland (FHNW), Switzerland
Integrated Project Delivery (IPD) for Healthcare Projects: A Company-Specific Analysis	Awad Hanna University of Wisconsin-Madison Department of Civil and Environmental Engineering, USA
Creating Co-location Concepts Under Consideration of Hybrid Approaches in Construction Projects	Leonie Szyperski Yukon Projects GmbH, Karlsruhe, Germany
Role of Work Flow in Reducing Life Cycle Energy Consumption in Construction	Musab Jamal Maraqa Technion-Israel Institute of Technology, Israel
Exploration of Educational Backgrounds, Personality Traits, and Gender on Tendencies to Collaborate Among Owners, Architects, Engineers, and Contractors	Zofia Rybkowski Texas A&M University, USA
Improving Premanufacturing Phases in Off-Site Construction Through a Digitalization Approach	Claudio Mourgues Pontificia Universidad Católica de Chile, Chile
Perception of Project Management among Construction Workers: A Survey in Denmark	Søren Wandahl Aarhus University, Denmark
Managing User Requirements in Social Housing Upgrading	Samira Awwal University of Huddersfield, UK
Analyzing the Lean Principles in Integrated Planning and Scheduling Methods	Moslem Sheikhkhoshkar Université de Lorraine, CNRS, CRAN, Epinal, France
Analysing the Impact of Construction Flow on Productivity	Asitha Rathnayake University of Cambridge, UK
Managing Human-Centered Innovation within Target Value Design	Patricia Tillman The Boldt Company, USA
Waste: Why Economics Got It So Wrong, and What Could Be the Remedy?	Lauri Koskela University of Huddersfield, UK

Listed in Table 4 are the invaluable conference track chairs who orchestrated the double-blind review process for the technical conference. We are grateful for their substantial behind-the-scenes efforts.

Table 4: IGLC31 Conference Track Chairs

Track	**Track chair name and affiliation**
BIM and Enabling Lean with Innovative Technology	Wassim Al Balkhy Centrale Lille, France
Contract and Cost Management	Sean Mulholland United States of Air Force Academy, USA
Health, Safety and Quality	Fidelis Emuze Central University of Technology, Free State, South Africa
Lean and Green	Kristen Parrish Arizona State University, USA

Lean Theory	Olli Seppänen Aalto University School of Engineering, Finland
Learning and Teaching Lean	James Smith Brigham Young University, USA
Modular and Off-Site Construction	Mohamed Al-Hussein; Ghulam Muhammad University of Alberta, Canada
People, Culture and Change	Paz Arroyo DPR Construction, USA
Product Development, Value and Design Management	Frode Drevland Department of Civil and Transportation Engineering, Norway
Production Planning and Control	Farook Hamzeh University of Alberta, Canada
Production System Design	Mani Poshdar Auckland University of Technology, New Zealand
Supply Chain Management	Emmanuel Daniel University of Wolverhampton, UK

We would also like to acknowledge the efforts of those who voluntarily committed their time and expertise to review papers. The double-blind review process was made possible by 216 reviewers from 35 countries. The reviewers listed in Table 5 worked diligently to ensure that accepted papers represented the high standard traditionally expected of an IGLC conference.

Finally, we would like to recognize the efforts of the authors too, for rigorously addressing the reviewers' comments and improving the quality of their final submissions.

As with most construction projects, an international conference represents an enormous collaborative undertaking that engages multiple moving parts. It is nice to know that members of the IGLC community practice what we profess.

Speaking on behalf of my co-editors and assistants for these proceedings, it has been an honor and a privilege to be part of this exciting and intellectually vigorous, collaborative effort. --ZKR

Table 5: Reviewers

Name	Affiliation
Mona Abd Al-Salam	University of Technology Sydney
Mohammed Adel Abdelmegid	University of Leeds
Muhamad Abduh	Institut Teknologi Bandung
Abbey Dale Abellanosa	University of Alberta
Eyad Reda Aboseif	Cairo University
Mohamed - A A Abou El Fish	KEO International
Hisham Abou Ibrahim	Aalto University
Peter Adekunle	University of Johannesburg
Samuel Adekunle	SARChl in Sustainable Constr Mnmt. and Leadership in the Built Envir.
Sa'id Ahmed	Kingston University London
Rina Asri Aisyah	PT PP (Persero) Tbk
Opeoluwa Akinradewo	University of Johannesburg
Wassim Albalkhy	Centrale Lille
Otto Alhava	Fira Group Oy
Hamed Alikhani	Texas A&M University
Fatima Alsakka	University of Alberta
Sharina Alves	Jade University of Applied Sciences Oldenburg
Thais Alves	San Diego State University
Joseph Hakkinen Alves Santos	UFCG
Caroline Silva Araújo	Federal University of Bahia

Paz Arroyo	DPR Construction
Elnaz Asadian	Pennsylvania State University
Sigmund Aslesen	Veidekke
Mohamed Kamal Assaf	University of Alberta
Muhammad Atiq Ur Rehman	École de technologie supérieure
Emna Attouri	Bouygues construction
Samira Awwal	University of Huddersfield
Omar Azakir	University of Alberta
Anas Badreddine	University of Alberta
Glenn Ballard	University of California, Berkeley
Beda Barkokebas	Pontificia Universidad Católica de Chile
Enric Barkokebas Martins	University of Alberta
José Barros Neto	Universidade Federal do Ceará
Karina Bertotto Barth	Federal University of Rio Grande do Sul
Fernanda Saidelles Bataglin	Federal University of Rio Grande do Sul
Sheila Belayutham	Universiti Teknologi MARA
Fabrice Berroir	Luxembourg Institute of Science and Technology
Marco Binninger	weisenburger bau GmbH
Trond Bølviken	University of Agder
Frédéric Bosché	University of Edinburgh
Makram Bou Hatoum	University of Kentucky
Makram Bouhatoum	University of Kentucky
James Philip Broadhead	Offsite Focus
Maximilian Rolf-Dieter Budau	Karlsruhe Institute of Technology
Samer BuHamdan	NA
Daniel Butcher	United States Air Force Academy
Luis Felipe Cândido	Federal University of Ceará at Crateús
Alessandro Carbonari	Università Politecnica delle Marche
Jennifer Alejandra Cardenas Castaneda	University of Alberta
Karen Castañeda	Universidad Industrial de Santander
Amin Chaabane	Ecole de technologie supérieure
Krishna Chauhan	Aalto University
Xue Chen	University of Alberta
Imen Chikhi	IFCL
Randi Muff Christensen	COWI
Diego Cisterna	Karlsruhe Institute of Technology
Stephen Paul Coates	University of Salford
Ricardo Codinhoto	The University of Bath
Manoela Conte	Federal University of Rio Grande do Sul
Ype Cuperus	Delft University of Technology
Emmanuel Daniel	University of Wolverhampton
Bhargav Dave	VisiLean Oy
Renato Rafael Del Grosso Filho	Universidade Federal de Goiás
Venkata Santosh Kumar Delhi	Indian Institute of Technology Bombay
Sevilay Demirkesen Cakir	Gebze Technical University
Sahil Dhakla	BuiltVisor Private Limited
Regina Dias Barkokebas	University of Alberta
Janosch Manuel Dlouhy	BMW Group
Frode Drevland	Norwegian University of Science and Technology
Parastoo Eivazi Ziaei	University of Alberta
Jan Alarik Elfving	Skanska
Mahmoud Elsayed	University of Alberta
Fidelis Abumere Emuze	Central University of Technology, Free State
Atle Engebø	Norwegian University of Science and Technology
Andrews Erazo-Rondinel	Universidad Continental
Bernardo Martim Beck Da Silva Etges	Climb Consulting Group
Chao Fan	University of Alberta
Yanqing Fang	Tianjin University of Finance and Economics
Herman Kvale Ferstad	Norwegian University of Science and Technology
Anne Fischer	Technische Universität München
Eric Forcael	Universidad del Bío-Bío
Carlos T. Formoso	Federal University of Rio Grande do Sul
Alejandro Javier Garcia De Taboada	Pontifical Catholic University of Peru
Nelly Paola Garcia-Lopez	Universidad de los Andes
Bruno Gazzola Antonini	Federal University of Rio Grande do Sul / Climb Consulting Group
Danial Gholinezhad Dazmiri	University of Alberta
Christy P. Gomez	Universiti Tun Hussein Onn Malaysia

Sulyn Cossett Gomez Villanueva	University of California, Berkeley
Jorge Antonio Gonzalez De Cossio Paez	ITN de Mexico
Elizabeth Ann Gordon	DPR Construction
Christopher Görsch	Aalto University
Anukriti Gupta	CEPT University, Ahmedabad
Laura Gutierrez Bucheli	Monash University
Douglas Comassetto Hamerski	Federal University of Rio Grande do Sul
Eran Haronian	Ariel University
Nicholas Michael Heier	Arizona State University
Darius Heller	University of Stuttgart
Fernando Lazcano Hernández	Benemérita Universidad Autónoma de Puebla
Rodrigo F. Herrera	Pontificia Universidad Católica de Valparaíso
Eilif Hjelseth	Norwegian University of Science and Technology
Matthew Ikuabe	University of Johannesburg
Eduardo Luis Isatto	NORIE/UFRGS
Anas Itani	University of Alberta
Tony Jacob	Constask Management Solutions LLP
Nathan George Owen Johns	Birmingham City University
Hrishikesh Sanatkumar Joshi	Indian Institute of Technology, Madras
Manuel Jungmann	Technische Universität Berlin
Tuuli Jylhä	Aalto University
Mayssa Kalach	American University of Beirut
Bo Terje Kalsaas	University of Agder
Ali Karakhan	University of Baghdad
Mahmoud Karaz	Universidade do Minho
Salam Khalife	University of Alberta
Suryeon Kim	Texas A&M University
Yong-Woo Kim	University of Washington
Ola Lædre	Norwegian University of Science and Technology
Camilo Ignacio Lagos Crua	Pontificia Universidad Católica de Chile
Eelon Mikael Lappalainen	Aalto University
Svenja Lauble	Karlsruhe Institut für Technologie
William Miguel León Daza	Universidad de los Andes
Jon Lerche	Aarhus University
Canlong Liu	The University of Auckland
Min Liu	Syracuse University
Sebastiano Lombardo	BI Norwegian Business School
Paramjit Singh Lota	VisiLean
Tulika Majumdar	Stanford University
Zeina Makram Malaeb	University of Alberta
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Trevor Mcsharry	Atlantic Technological University
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Roseneia Rodrigues Santos Melo	Federal University of Bahia
Ricardo Mendes Jr	Federal University of Paraná
Samaneh Momenifar	University of Alberta
Alan Mossman	The Change Business
Claudio Mourgues	Pontificia Universidad Catolica de Chile
Sean M. Mulholland	United States Air Force Academy
Koichi Murata	Nihon University
Danny Murguia	University of Cambridge
Muktari Musa	LeanBuild Limited
Kristoffer Brattegard Narum	Norwegian University of Science and Technology
Tran Duong Nguyen	Georgia Institute of Technology
Babatunde Fatai Ogunbayo	University of Johanesburg
Svenja Oprach	Karlsruher Institute of Technology
Kenneth Otasowie	University of Johannesburg
Omar Owais	Auckland University of Technology
Kristen Parrish	Arizona State University
Sigurd Brunstad Paulsen	Multiconsult AS
Barbara Pedo	University of Huddersfield
Hugo Sefrian Peinado	Federal University of Bahia

Antti Peltokorpi	Aalto University
Ari Pennanen	Haahtela Group and Aalto University
Fernando Gabriel Lopes Pereira	Climb Consulting Group
Cristina Toca Pérez	Aarhus University
Flavio Augusto Picchi	Unicamp / LIB
Tainara Pires Nievola	UFPR - Universidade Federal do Paraná / Tecverde Engenharia S.A.
Mohammad Poshdar	Auckland University of Technology
Elyar Pourrahimian	University of Alberta
William Power	DPS Group
Natália Ransolin	UFRGS
Asitha Rathnayake	University of Cambridge
Ana Virginia Reinbold	Aalto Univertity
Yanh Ribeiro	GEQUALTEC - Instituto da Construção
Jaakko Markus Riekki	Aalto University
Francesco Livio Rossini	Sapienza University of Rome
Rafael Sacks	Technion – Israel Institute of Technology
Arsalan Safari	Qatar University
Abhay Saini	Indian Institute of Technology Bombay
Luis Arturo Salazar	Universidad Técnica Federico Santa María
Diana Salhab	University of Alberta
Stephanie Salling	Aarhus University
Saad Sarhan	University of Lincoln
Annett Schöttle	Refine Projects AG
Felix Schulze	Free University Bozen-Bolzano
Bolivar Senior	Colorado State University
Olli Seppänen	Aalto University School of Engineering
Sheyla Mara Serra	Universidade Federal de São Carlos
Li-Or Sharoni	Technion – Israel Institute of Technology
Lynn Shehab	University of Alberta
Moslem Sheikhkhoshkar	University of Lorraine
Jeferson Shin-Iti Shigaki	The University of Tokyo
Wenchi Shou	Western Sydney University
John Skaar	University of Agder
Sol Skinnarland	Østfold University College
James Packer Smith	Brigham Young University
Sahar Soltani	Monash University
Alvaro Augusto Sosa Córdova	Universidad Peruana de Ciencias Aplicadas
Dominik Steuer	Karlsruhe Institute of Technology
Matt Stevens	Western Sydney University
Leonie Zoe Szyperski	Yukon Projects GmbH
Martin Taggart	Galway-Mayo Institute of Technology
Marcus Costa Tenório Fireman	Federal University of Rio Grande do Sul
Iris D. Tommelein	University of California, Berkeley
Olav Torp	Norwegian University of Science and Technology
Bo Christian Trollsås	AF Gruppen
David Umstot	Umstot Project and Facilities Solutions, LLC.
Kalyan Vaidyanathan	Nadhi Information Technologies Pvt. Ltd.
Tuomas Tapio Valkonen	Aalto University
Koshy Varghese	Indian Institute of Technology Madras
Alejandro Vásquez-Hernández	Pontificia Universidad Católica de Chile / Universidad EAFIT
Valeria Veronica Vecchio	University of Alberta
Senthilkumar Venkatachalam	Indian Institute of Technology Palakkad
Rafael Vigario Coelho	University of California, Berkeley
Kenneth D Walsh	George Mason University
Brad Wambeke	United States Air Force Academy
Soren Wandahl	Aarhus University
Yu Wei	University of Alberta
Timson Yeung	Technion – Israel Institute of Technology
Omar Zegarra	Consultant Services
Tadesse Ayalew Zelele	Addis Ababa University
Yuxuan Zhang	University of Alberta
Hua Zhong	Nottingham Trent University

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WASTE: WHY ECONOMICS GOT IS SO WRONG, AND WHAT COULD BE THE REMEDY?

Lauri Koskela[1], Glenn Ballard[2] and Trond Bølviken[3]

ABSTRACT

A paradigm shift occurred in economics in the middle of the 20th csentury. According to the old paradigm, economics studies the determinants of wealth. The new paradigm, called neoclassical economics, posits that economics studies behaviour under scarcity of resources. A corollary of the new view is that people and organisations can be assumed to make optimal, best possible, decisions regarding the scarce resources.

The old paradigm of economics recognized waste as a factor influencing wealth. The new paradigm, focusing on optimal allocation of resources, did not apply the notion of waste. The Nobel laureate economist Stigler went in 1976 even further and claimed that waste is not a useful concept in economic theory, though he admitted the occurrence of waste, which he narrowly defined as a foregone product that can be obtained for less than its cost.

The 1976 paper of Stigler is critically assessed. Three major shortcomings are found. First, waste is ubiquitous in economic activities, whereas Stigler downplayed its significance. Second, waste can occur irrespective of the context, whereas Stigler insisted that waste occurs in the context of market exchange. Third, decision usually needs to be implemented in the material world, and waste often emerges in this implementation. Stigler considered decisions without taking implementation into account.

To rectify the shortcomings in the economic conception of behaviour under scarcity, a new conception is offered. It is based on the recognition of three different types of waste in relation to a decision: background waste, non-optimality of the decision, and foreground waste. There should be an attempt to reduce or to eliminate all three types of waste. The new conception implies that the starting point of neoclassical economics has been seriously wrong.

KEYWORDS

Economics, waste, optimum, scarcity, Stigler

INTRODUCTION

The neoclassical economic theory assumes that firms make optimal decisions under scarcity. Thus, in their production, the maximum possible output from given amounts of inputs is gained. Firms are thus operating on their production frontier, determined by their production function and representing the maximal production opportunities. Obviously, firms differ regarding their efficiency; this is explained by assuming each firm to have its own production frontier.

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However, firms can move their production frontier by deciding to invest into new technology (this concept includes also knowledge). (Stigler 1976).

In the discipline of production management, there has been another conceptualisation of production, where the concept of waste is used. Waste refers here to avoidable costs of production (or any other activity in the firm), for example costs which can be attributed to poor quality. The efficiency differences between firms using the same technology may be explained by different levels of waste. These waste costs can be avoided or at least reduced by appropriate training, management, etc. However, first the root causes of waste need to be investigated, for selecting appropriate countermeasures. Thus, problem-solving is emphasised as a key activity. All in all, the key significance of waste is that it represents unexploited potential for improvement.

These two conceptions of production are starkly contradictory: one assumes that firms continuously make optimal decisions and gain maximal output, the other views that there always exists, more or less, waste in operations, representing avoidable costs. This contradiction has attracted surprisingly little scholarly attention. However, in a recent call for economics of climate change and related change in economics (Stern 2022), a new research area for economics is proposed: "There are all kinds of inefficiencies that exist in our economies and we must try to to understand their nature and origins and how to overcome them."

This paper endeavours to respond to Stern's call. The treatment of inefficiency, waste, in economics is critically reviewed and its serious errors and weaknesses are pinpointed. Based on this, a new conception of behaviour under scarcity is proposed. This conception deals with decisions and waste in the same framework, and in so doing, offers itself as one new starting point for economics for understanding inefficiencies. This may sound recklessly and unrealistically ambitious. However, as Attenborough states (2021): "Economics is a discipline that shapes decisions of the utmost consequence, and so matters to us all."

The paper is structured as follows. The following section gives a historical account on the understanding of waste in economics. Then, the most influential, and also most detailed theoretical concept of waste in economics, originated by Stigler, is critically evaluated. Next, the current understanding of the notion of waste in the context of economic practice is explored. To rectify the found shortcomings of the concept of waste of neoclassical economics, and to remove the current confusion around this notion, a new conception of behaviour under scarcity is then devised.

WASTE IN ECONOMICS

WASTE IN ECONOMICS UP TO MID 20TH CENTURY

Up to the 1930's, the common definition of economics stated that it deals with the causes of material welfare, especially production and distribution (Robbins 1932). In this framework, waste was acknowledged as a worthy topic of the economic science, but there was little theoretical work on it.

A new paradigm of economics, now called neoclassical economics, did a breakthrough in the period 1935 – 1950. One leading idea was that economics is a science addressing behaviour under scarcity – production was excluded from the subject-matter of economics. In an influential essay, Robbins (1932) states: "But when time and the means for achieving ends are limited and capable of being distinguished in order of importance, then behaviour necessarily assumes the form of choice." It is of course prudent to assume that economic agents try to make the best decisions (choices) they can, given their circumstances. However, another branch of the economic theory gave even further support to the idea of optimal decisions. In analyses of perfect competition, assumptions closely related to optimal decisions were made from early on. Such assumptions included the following (Knight 1921):

Economic agents act with complete rationality

They know what they want

They know absolutely the consequences of their acts when they are performed, and perform them in the light of the consequences

The mathematization of the neoclassical economic theory gave a further boost to the idea of optimal decisions. Especially, Samuelson's (1947) influential synthesis of the neoclassical theory contained the axiomatic assumption of economic agents making optimal decisions, for maximizing profit or utility under the ubiquitous scarcity. The concept of waste does not fit into this conception; waste implies that decision-making has not necessarily been optimal.

The production management-based conception was dominant in the first part of the 20th century: waste was discussed in writings on economics, management, production and policies. However, the neoclassical economic theory started to be propagated in the 1930s and diffused in the next decades. Along with this, the usage of the notion of waste diminished; it was simply not needed in discussions focusing on optimal production. Along with the proliferation of neoclassical economics, the usage of the term waste declined both in economic literature and economic policy. It is illustrative that when President Johnson in 1964 launched a war against waste in administration, the Time magazine commented that he felt "folksy pride" when describing efforts to eliminate waste (Time 1964). The term of waste started to be positioned as a word used only in colloquial contexts.

COMPETING VIEWS IN ECONOMICS ON OPTIMAL DECISIONS AND WASTE

Nevertheless, the everyday observations on less than optimal decisions and inefficiencies of course continued in the context of business, households, etc., and there were attempts to incorporate such findings into economic theory.

An early example is provided by Simon (1955), who argued that people do not search for the absolute optimum, but rather satisfice, that is, stop the search when a sufficient and satisfactory option has been found. Especially, Simon pinpointed that the concept of rational behaviour should be compatible with the access to information and the computational capacities actually possessed by the "economic man". Based on this seminal contribution, a new branch of economics, namely behavioural economics, emerged. However, behavioural economics has not been able shake the dominance of the neoclassical theory.

Among the many modes of behavioural economics, one has been directly focused on waste, namely Leibenstein's (1966) theory of X-efficiency, which explains the formation of waste mainly through motivational factors. According to Leibenstein, "where the motivation is weak, firm managements will permit a considerable degree of slack in their operations and will not seek cost-improving methods".

Triggered by Leibenstein's theory, which challenged the neoclassical orthodoxy, the noted economist and Nobel laureate Stigler published an article that defined waste from the neoclassical viewpoint as error, and then claimed, in essence, that waste is not a useful economic concept (Stigler 1976). Next Kirzner (1978) presented his concept of waste, also based on the idea of waste as error in decision; however he rejected Stigler's view that the amount of waste is negligible. Somewhat later, Williamson (1991) forwarded the claim that failures of alignment of transactions and their governance structures create waste.

These competing conceptions of waste in economics are summarised in Table 1. Out of the four conceptions, only Stigler's contribution, which closely relates to the dominant neoclassical doctrine, has had long term influence. Therefore, it is focused on in the remainder of the paper.

Table 1: Competing conceptions of waste in economics

Originator	Cause of waste	Prevalence of waste	Reduction/elimination	Conceptual framework
Leibenstein, 1966	Lacking motivation or incentives (and a variety of factors influencing these)	Considerable: "…people and organizations normally work neither as hard nor as effectively as they could."	Competitive pressure, adversity, force of example	Neoclassical economics, psychology
Stigler, 1976	Error in decision; non-optimal behaviour	Negligible: can be abstracted away	Costs and prices incite to correct decisions	Neoclassical economics
Kirzner, 1978	Error in decision	Very common: "enormous scope for improvement exists"	Through entrepreneurship	Austrian economics
Williamson, 1991	Failures of alignment of transactions with governance structures	The assumption of firms working on their production function and maximizing profits is an egregious oversimplification.	"…better organizational form; better internal incentives and controls; better alignment of the contractual (interfirm and intrafirm) interfaces"	Institutional economics, especially transaction cost economics

STIGLER'S ATTACK ON WASTE IN 1976

In his much cited and influential[4] paper, Stigler (1976) seems to want to explicitly push waste out of economics. In doing so, he comes to define waste from the economic viewpoint in a useful detail. In the following, this attack on waste is presented and critically analysed.

DEFINITION OF WASTE

According to Stigler (1976), "waste is a foregone product that could be obtained for less than its cost". This definition is somewhat cryptic[5] as well as vague and deserves to be clarified through an example.

The grocery shop that is frequently used by the first author has an oven where bread, rolls, etc., are daily baked from frozen dough. For example, a multigrain roll has the price of 85 pence. However, if there are rolls still available after 19.00 o'clock or so, the price is reduced to 5 pence. Most probably this is below the cost of the roll. Thus, the question is about waste, in Stigler's sense.

It can be observed that Stigler wants to define waste in connection to a possible or realised market exchange. However, in doing so, he excludes waste that occurs in organisations not offering products for market, such as governmental organisations or households. Also, because

[4] Perelman (2011) writes: "Realizing that Leibenstein's idea of X-efficiency represented a serious threat to abstract price theory, Stigler (1976) rose to the occasion, pulling out all the stops. In terms of rhetorical success, Stigler's combination of brilliance and bluster mostly carried the day."

[5] The word "foregone" requires interpretation. The probably most common meaning of a "foregone product" refers to a product that was not purchased although seriously considered. However, here the question is about another meaning of "foregone", namely previous or past. Thus "foregone product" refers to a product that has been (previously) produced, and is available after a time lag for less than its cost. Namely, a producer will not knowingly create a wasteful product; time is needed after the act of production for realising that a reduced price is appropriate.

waste, as defined by Stigler, must be visible in a product, wastes (in the generic sense of the word) occurring inside the productive processes may not get visible[6].

Moreover, alone from our example, questions that challenge the logic of Stigler's definition of waste arise: Is it waste if the shop would not reduce the price in the evening, and a roll does not get sold? If a customer buys a roll, but just forgets to eat it in time, and has to put it into the garbage can or feed to birds, is that waste[7]?

Stigler does not explain why he has selected this definition for waste. However, a possible inspiration is the purpose given to production in the economic theory. According to Frisch (1965), production in the economic sense means an attempt to create a product which is more highly valued than the original input elements. Obviously, this purpose is not fulfilled if a foregone product could be obtained for less than its cost.

CAUSES OF WASTE

Stigler recognises two causes of waste: (1) Plans rested upon erroneous predictions; (2) The economic agent is not engaged in maximizing behavior.

Even if the word is missing in these two causes, the question is about decisions; regarding the first cause, assumptions of a decision that turn out to be wrong, and regarding the second cause, decisions that are not made in an optimal manner.

In our illustrative example, waste arises if the predicted daily demand for rolls turns out to be wrong (erroneous prediction), or if the number of rolls produced is not based on empirical patterns of demand (that is, the behaviour is not optimising).

The second cause, of course, represents the ideas of Simon (1955), Leibenstein (1966) and others who have claimed that economic agents are not making optimal decisions.

In critical analysis, a significant oversight is that Stigler sees waste causation only in terms of decisions, belonging to the world of ideas. Waste will emerge when a decision is implemented in the material world – this is not covered by Stigler at all. An implication is that Stigler fails to see a number of important causes of waste in the material world, such as variability of productive processes (as studied in Hopp & Spearman's Factory Physics (2011)).

AMOUNT OF WASTE

Stigler comments the amount of waste regarding the first cause above, decisions being based on erroneous assumptions. According to him, "its magnitude is subject to control". He does not justify this claim. He does not present empirical evidence on the amount of waste. Nevertheless, he seems to conclude that the amount of waste is negligible and can be abstracted away.

PLACE OF WASTE IN THE ECONOMIC THEORY

Regarding the first cause of waste, Stigler states: "Waste is error within the framework of modern economic analysis, and it will not become a useful concept until we have a theory of error".

Regarding his second cause, he says: "Until one is prepared to take the mighty methodological leap into the unknown that a nonmaximizing theory requires, waste is not a useful economic concept."

Thus, in either case, "waste is not a useful economic concept". The message is clear: the occupation with waste should thus stop in economics.

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[6] An analogous situation has been noted by Koskela and Tommelein (2009), who claim that opportunities for sustainability improvements may be invisible when production is looked at from the economic viewpoint, as a black box transformation.

[7] This example also illustrates that "waste" is an abstract man made construct rather than a phenomenon. What is waste depends on the subject observing the setting.

REDUCING OR ELIMINATING WASTE

Nevertheless, Stigler gives, in passing, one direction that, besides solving the original problem of Leibenstein, namely productivity differences between firms, could be used for reducing or eliminating waste. He writes: "No attention has been paid by economists to the analysis of the optimal amount of technological knowledge that a firm should possess." He illustrates this through a dense sketch concerning two farmers with different productivity: "In neoclassical economics, the producer is always at a production frontier, but his frontier may be above or below that of other producers. The procedure allocates the foregone product to some factor, so in turn the owner of that factor will be incited to allocate it correctly".

The procedure outlined by Stigler seems to be based on three principles. Firstly, the starting point here is the "foregone product", which for whatever reason has been observed as problematic. For example, the company can get the products sold only by having a lower price than the main competitor, or there is waste (in Stigler's sense) associated to the product. Either way, for the particular foregone product, the problematic feature is identified.

Secondly, then, that problematic feature is "allocated" to some factor of production. These include, manpower, land (raw materials), capital (machinery) and technology. In neoclassical economics, production is a black box, meaning that only inputs (factors) and outputs (foregone products) are visible. Thus, remarkably, the problematic feature of a product is associated, through the black box, to a factor. Obviously, some kind of an inference backwards (regression) is carried out.

Thirdly, the owner of that factor will then make a "correct" decision. It can be assumed that this is the optimal decision.

This Stigler's procedure is closely based on the doctrine of neoclassical economics: production gets managed, through optimal decisions, by prices and costs. However, there is one exception: as far as we know, regressive inferences from outcome to cause are not part of the conceptual framework of economics. Looking at the proposed framework from a practical viewpoint, the central question is how the right factor can be identified when production is seen as a black box. Say, quality problems are identified in the products: it may be impossible to determine whether the cause lies with materials, manpower, equipment or knowledge without opening the black box and investigating the process (flow) of production.

OVERALL ASSESSMENT OF STIGLER'S CONCEPT OF WASTE

Above, features of Stigler's conception of waste have already been critically assessed; here the conception is assessed as a whole.

Stigler, as a leading proponent of the neoclassical economic theory, defines and discusses the notion of waste and finds that is is not a useful concept for economic theory. Unfortunately, Stigler's conception of waste is distorted and biased, and his conclusions are wrong. Three major shortcomings in his conception can be identified:

- Stigler's narrowly defined waste is unavoidable, however it's magnitude can be subject to control so that it can be abstracted away; we argue that waste is ubiquitous and of such magnitude that it cannot be abstracted away.
- Stigler defines waste in the context of decisions and market exchange; we argue that waste can occur irrespective whether the context is decisions and market exchange or not.
- Stigler does not take into consideration that decisions often, if not usually, need to be implemented in the material world; we claim that it is also here that waste can occur.

These arguments lead us to contend that waste, inefficiency, should be fully incorporated into economic theory.

CURRENT PRACTICAL IMPACT OF ECONOMIC TREATMENTS OF WASTE

Above, the treatment of waste in the neoclassical economic theory has been discussed. It is also of interest how waste is currently dealt with. In the following, three cases of current treatment of waste in the practice (or practice-oriented teaching) of economics are discussed. Although the sample is small, the cases give a cogent picture of the situation.

WASTE IN HEALTHCARE

In 2017, the the Organisation for Economic Co-operation and Development (OECD) published a report on healthcare waste. In that report, two principles for reducing waste are highlighted:

"• Stop spending on things that do not improve health – for example, unnecessary surgeries and clinical procedures.

• Swap inputs and change approaches when less pricy alternatives of equal value exist."

The first principle would seem to suggest deciding to eliminate waste. In turn, the second principle interestingly recommends making optimal decisions.

The suggested implementation of waste reduction is summarised as follows: "…recognizing the existence of the problem, developing tools to assess its scale, convincing and incentivizing stakeholders to change their behaviour are all part of the solution."

Thus, waste is seen to be caused by stakeholders' decisions and behaviour, in compliance with economic theory. However, in contradiction to that theory, it is implicitly admitted that decisions are not necessarily optimal, causing waste.

FOOD WASTE

The attention given to food waste has triggered recent research in economics, given that "there exists no foundational economic model of food loss and waste for consumers, processors, intermediaries and farmers based on first principles" (Drabik, de Gorter and Reynolds 2019). This lack of a foundational model for food waste is of course related to situation that there is no foundational economic model of the emergence of waste in general. Given this, economists try to use existing economic theory. For example, Lusk and Ellison (2020) consider it self-evident that food waste is an economic phenomenon, related to consumer decisions:

> In fact, many analyses of food waste seem to conceptualize food waste as a mistake or inefficiency, and in some popular writings a sinful behaviour, rather than an economic phenomenon that arises from preferences, incentives and constraints.

In their view, "it is imperative to view the waste decision like any other decision – one with costs and benefits". However, the insistence of seeing food waste because of consumer decisions unavoidably leads to the contradiction mentioned above: the assumption of optimal decision-making does not leave room for waste. Lusk and Ellison (2017) are at a loss to explain this:

> A challenge with the studies that model waste as an outcome of consumer maximization decisions, insofar as informing public policy, is that the decision to waste, at least from the perspective of the consumer, is optimal. If so, it is unclear what role there is for public policy or public education aimed at reducing food waste. If "waste" is a result of an optimal decision, forcing a lower level of waste would necessarily harm consumers.

WASTE AS DISCUSSED IN A TEXTBOOK FOR CONSTRUCTION ECONOMICS

In his popular textbook on construction economics, Myers (2004) says:

> In any free market economy businesses will never waste inputs. A business will not use 10 units of capital, 10 units of labour and 10 units of land when it could produce the same amount of output with only 8 units of capital, 7 units of labour and 9 units of land.

This of course contrasts to empirical observations stating that waste is omnipresent in construction (Arbulu & Tommelein 2002).

CONCLUSIONS

An overview on the approaches to waste in the three cases considered is given in Table 2.

Table 2: Conceptualisation of waste in the considered three cases.

Context of waste	What is the cause of waste?	Are decisions optimal?	How can waste be reduced or eliminated?	Is waste prevalent?
Healthcare	Decisions	No	Decisions	Yes
Food	Decisions	Yes	Decisions (?)	Yes
Construction management	Decisions (but only in principle)	Yes	No need	No

In all three cases, waste is seen to be caused by decisions, and correspondingly decisions are held as the means for waste reduction (if this is needed). In two cases, decisions are seen to be optimal, whereas in one case, this is denied. In turn, waste is seen to be prevalent in two cases, whereas in one case, the occurrence of waste is denied. Thus, beyond the idea that waste is caused and reduced by decisions, there is a major confusion regarding the existence and causes of waste.

The analysis of these three cases shows that the topic of waste has been left fallow in economics: "…economists have mainly assumed the problems of waste away…" (Williamson 1991). Arguably, Stigler's paper which concluded that waste is not a useful concept has contributed to this situation. All in all, this analysis of current economic application of the notion of waste supports the view that a clarification of this notion is badly needed.

BEHAVIOUR UNDER SCARCITY: A NEW CONCEPTION

CONSTRUCTING THE NEW CONCEPTION

Above, three major shortcomings in Stigler's conception of waste were identified as well as correctives, which include:

- waste is ubiquitous and of such a magnitude that it cannot be abstracted away but rather one should continuously act on it
- waste due to a decision can occur irrespective whether the context is market exchange or not.
- decisions often, if not usually, need to be implemented in the material world; it is also here that waste can occur.

A new conception for decision-making behaviour under scarcity is needed where all inefficiencies are covered. Thus, waste before a decision, waste directly originated by that decision, and waste possibly occurring after the decision, as an indirect consequence of it, have to be addressed. It is proposed that these are called background waste, decision related waste and foreground waste. This conception is compared to Stigler's conception in Table 3, and its different elements are discussed in the following.

Table 3: Comparison between the waste types in the new conception for behaviour under scarcity and in Stigler's conception.

Waste type	The new conception	Stigler's conception
Background waste	Waste existing prior to the decision, and affecting that decision (through general resource scarcity or as a factor in the decision)	Not covered
Decision-related waste	Outcome of a non-optimal decision	Foregone product can be obtained for less than its cost
Foreground waste	Waste occurring in the implementation of a decision	Not covered

BACKGROUND WASTE

Background waste consists of the waste "normally" emerging in the activities of an organisation. This occurrence of waste adds to costs, and relatively, adds to the scarcity of resources the organisation is experiencing. Williamson's (1991) first order economising addresses this kind of waste, whereas second order economising is about optimal allocation of resources.

Authors in production management argue that waste should be continually reduced. Especially, the approach of continuous improvement (Imai 1986), *kaizen*, focuses on background waste.

What is then the relation between background waste and a decision? Robbins defined economics in terms of scarce means in view of our limitless ends. First, the accumulated savings from continuous improvement and reduction of background waste diminish the scarcity of means: simply, there is more money for every need considered important. Secondly, background waste is also related to our ends. If our household can reduce the food waste, we would need to buy or otherwise acquire less food. Note that the relation of background waste reduction to a decision is generic in the first case. Instead, in the second case, decision-specific waste reduction (that is, waste related to an end should be reduced) is needed.

DECISION-RELATED WASTE

All non-optimal decisions lead to waste. The question may be about assumptions that turn out to be wrong, calculation error, etc. Surely decisions need to be as good as possible, based on the factors that are known at the time of making that decision. As it is well-known, uncertainty about the future, incomplete information on the current state and deficient understanding of the phenomena dealt with in the decision make it difficult if not impossible to determine the optimal, best possible, decision in practice.

FOREGROUND WASTE

Decisions represent mental commitments – however most decisions need to be implemented in the material world. During this implementation, waste can occur. This is called foreground waste as the room for it is created by the relevant decision. By not acknowledging the implementation of decisions, economics fails to recognise this type of waste.

The mundane example of buying milk on a hot summer day provides an example. When deciding to buy, we need to anticipate how long it would take to have the milk brought to the fridge, to avoid it being spoiled. Another example is offered through the case that a client decides to start a construction project. That decision leads to a multitude of subsequent activities in the material world, as well as to a multitude of subsequent decisions in the world of ideas, and the possibility of waste is lurking everywhere.

ILLUSTRATION

Let us illustrate the new conception through the case of a hospital project.

Background waste

The OECD report (2017) and other literature gives abundant evidence on the prevalence of waste in healthcare settings, including hospitals. The reduction of such background waste is already a reality in some hospitals (Virginia Mason Institute 2021, Reijula & Tommelein 2012). By reducing operational costs, there is more room for capital investment.

On the other hand, some background waste may be directly related to an upcoming decision. Through a new facility design, the daily walking time of the nursing staff may be reduced. By reducing re-admissions, the number of beds needed may be reduced.

Decision-related waste

Decision-related waste is mostly related to the continued need for the facility in question. Thus, the correctness of assumptions and predictions accentuates.

Foreground waste

Hospital design, as such, is a complex endeavour, and proceeds under many uncertainties. The best available approaches need to be used for avoiding waste. Life cycle thinking and future-proofing (Memari et al. 2023) can be mentioned as promising countermeasures regarding issues emanating from the long life of the facility and the uncertainties surrounding it. However, the primary consideration should be given to approaches and methods addressing waste in design and construction, for the sake of continuous improvement during these stages and beyond (Koskela & Ballard 2021). Especially the Target Value Delivery procedure (Ballard 2020) has turned out to be instrumental for reducing avoidable cost. The commonly achieved savings, in the region of 10 – 30 %, give a manifest proof of the existence and magnitude of foreground waste.

CONCLUDING DISCUSSION

The idea of scarcity of resources as a starting point for economising, and indeed, economics, is fundamental. The conclusion drawn from this has been that resources should be allocated to different uses in the best possible way, optimally. However, there is a critical shortcoming in this reasoning: for its part, resources are scarce because we are wasting them. As Williamson (1991) argues, reduction and elimination of waste should be the primary form of economising, only after that come optimal decisions.

However, economics has acknowledged only optimal decisions, and been silent on the need to tackle waste. Because of the immense influence economics has had from the middle of the 20^{th} century onwards, this has had considerable consequences on many fronts. Let us just remind that many of the sustainability problems are waste problems, starting from the considerable food waste to the inefficient use of energy resources.

It is noteworthy that the concept of waste has never been explicitly and convincingly argued to be useless in economising; it has just been incompatible with the theoretical constructions of neoclassical economics, and attempts to import waste into the economic theory have been aggressively shot down, with strong rhetoric but weak justification.

The suppression of the concept of waste in economics is also related to the neglect, in economics, of a phenomenon which shows perhaps the majority of waste: production. Background waste exists in all activities of an organisation, including especially production. Much, if not most foreground waste likewise falls into production. Thus, the exclusion of production from economics, which was strongly propagated by Robbins (1932) and then realised through the proliferation of neoclassical economics, was a grave mistake.

The declared purpose of academic economics is to explain and predict; however, in practice, the economic theory is taken as a description of economic phenomena, and as a normative guideline. The many books of managerial economics are examples of the latter. Waste being absent both in the description and in the normative guidelines has led to a situation where waste reduction is not recognised as a valid and necessary line of practical action. Furthermore, without awareness of the possibility of the emergence of waste, it may be that lines of action based on economics have actually increased waste.

The new conception of behaviour under scarcity, if accepted, arguably leads to the need to reassess the neoclassical economic theory; there is no visibility on all implications now. However, a more immediate and important consequence is that the normative guidance on the part of economics needs to be changed to cover both optimal decision and waste reduction.

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EXAMINING THE GAP BETWEEN CONSTRUCTION SOFTWARE MODULES AND LEAN CONTRACTOR PRACTICES

Matt Stevens[1] and Kola Olayiwola[2]

ABSTRACT

Construction contracting software has existed for over three decades while this industry has suffered many of the same problems, such as disproportionately high bankruptcy rates and stagnant multifactor productivity. This paper reviewed industry software operating manuals and conducted executive interviews to examine a significant blind spot in the Australian construction industry. This gap is the lack of support their products give to the accepted practices of contractors' operations. Software developers appear to have not pursued the clear Lean ideal of "perfection". All their client's needs and wants have not been met. Many small and medium-sized contractors rely on customising computer spreadsheets to calculate supporting information needed to execute some practices. In contrast, others are unaware of the methods or have not taken this additional step. The researcher has identified eight specific processes to research software firms' product literature to discover the extent of the gap. The sources of these issues are many; however, tailoring construction software to enable effective practices while "hardwiring" them into a company's process could lessen industry problems. Lean Construction researchers have asserted that this is the potential of Information and Communication Technology through a "push" approach.

KEYWORDS

Construction software, contractor ICT, built environment technology

INTRODUCTION

The construction industry globally has been slow to adopt Information and Communication Technology (ICT) even though projects generate much information that must be processed timely and securely stored. Additionally, construction contracting is more complicated than any other sector due to one-of-a-kind production (Andújar-Montoya et al. 2020). The industry has many ad-hoc production control methods, most of which are informal, fostering uncertainty that prevents smooth production flow (Dave et al. 2016).

Rapid standardisation and automation are highly improbable without software tools and digitalised business processes (Matt and Rauch 2014). Nevertheless, the transformational potential is apparent to many researchers in the standardisation and automation of processes and workflows in both the planning and execution stages. Moreover, practitioners and scientists have made efforts to improve the current situation (Faghihi et al. 2015).

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Researchers and software vendors have provided many reasons for the low implementation of ICT solutions in the industry, such as high acquisition cost, ongoing investment, and mastery time it requires. However, this paper asserts that there may be another reason, it does not possess significant value (total cost versus profit) for contractors over generic software such as spreadsheets. Standardisation and automation can be provided by using accessible spreadsheets.

Approximately 3/4 of contractors physically construct the work (subcontractors or specialty contractors), and more than 95% employ 20 employees or less, qualifying as Small-Medium Enterprises (SME) (ABS 2022). These SMEs deliver significant value to project owners by installing materials in compliance with the specifications. This is where ICT can make the most industry impact. Increasing value-for-money for all more will adopt more information technology; thus, performance in critical areas such as safety, quality and productivity should improve. Technology appears to be the logical solution enabler. Improvement seems highly probable if it can be tailored through construction software recoding, application programming interface or a mobile computing application. Not creating these well-established and accepted practices in the industry standard software will contribute to the continuing malaise.

LITERATURE REVIEW

This literature review examined the nexus between construction contracting accepted practices and construction software modules.

INDUSTRY CONTEXT

Construction is characterised by factors that affect the schedule, forecasting of resources and quality. It is considered complicated and information critical based primarily on the accuracy of interpreting varied issues based on a professional's body of work (Wu et al. 2012). Prior studies have identified the construction industry's unique working methods as the main barrier to implementing an industry improvement (Dubois and Gadde 2002).

Lean Construction researchers have recognised that expected productivity can decline due to conflicting goals between individual trades and the project (Sack et al. 2010). Hartmann et al. (2012) suggest that project teams must align their work processes to the new "collaborative and integrated ways of working" including using ICT to reach these goals. Contractors – main and sub - typically work with constrained resources to complete different projects simultaneously, making portfolio management a critical skill. The organisation enables well-executed projects. They try to optimise these resources, which requires thoughtful planning to execute interdependent tasks well (Lasni and Boton 2022). Best construction practices help manage multiple processes that must work simultaneously to make a construction firm consistently profitable and raise its position on the Risk-Reward Curve (Stevens 2012). Constant planning, as well as careful schedule monitoring, detailed decision-making, proactive problem recognition and, thus, earlier than needed solutions (Ahuja et al. 1994). However, according to the Australian government, multifactor industry productivity in that country has been stagnant for over two decades (Stevens and Smolders 2023)

A recent technological shift, such as Building Information Modelling (BIM), appears to be re-energising the focus on effective practices, including those considered Lean (Sacks et al. 2018); it enables project stakeholders to plan, design, review, program, cost or manage construction projects. This interactive process enhances the design end product (Kuiper & Holzer 2013). In addition, ICT can improve construction industry operational procedures, particularly planning and control (Martins et al. 2020). The most used goals for contractors revolve around time, cost, quality, profitability, customer satisfaction, safety, and sustainability (Fahri et al. 2015).

Construction managers must interpret and process voluminous data for proper up-to-date decision-making in effectively running a project. Therefore, the project's success depends on the increased reliance on technology. However, individuals' readiness to adopt technology has four dimensions: optimism, innovativeness, discomfort and insecurity. The four are independent; optimism and innovativeness encourage people to use and hold a positive attitude to technological products and services, while a lack of comfort and security prevent their adoption (McNamara, Shirowzhan & M.E. Sepasgozar 2022).

The research literature does not contain a rigorous review of ICT Technologies applied in the construction industry, although several have been proposed. There has been a fluctuating decline in articles since 2002, resulting in fewer publications in 2015. (Adwan and Al-Soufi 2016). Additionally, minimal research has been conducted to capture the issues barring technological adoption among small firms (Clermont et al. 2020) to help them identify their real needs and wants, including their challenges. This identification can help companies make changes and better address pressure from competitors (Lasni and Boton 2022).

SOFTWARE DEVELOPMENT AND UPGRADING HURDLES

Today, software development is conducted in a chaotic environment. For example, Holmstrom et al. (2012) found disordered and dynamic markets, complicated and uncertain customer demands, shorter development cycle time pressures, and Moore's Law effects in most software development projects. Notably, nine barriers in the industry dampen construction innovation, Also, this results in suboptimal investment in new ideas, including software development (Stevens and Smolders 2023).

There is no standard software development process due to the differing characteristics of the organisations, products, and projects. The process is contingent on the knowledge and experience of the software Research and Design staff and the organisational guidelines, including the economic ones they must work within (Choi et al. 2017). In many software development firms, product managers struggle to get well-defined customer perceptions, needs and wants. Often, software value and utility validation occur after deployment. Furthermore, learning from customers is neither typically formalised nor continuous. As a result, the selection and prioritisation of utilities become suboptimal, and products are misaligned from what the customers need or want (Fabijan 2015). Literature has established that the lack of programming management commitment has been one of the top reasons for the failure of Software Process Improvement (SPI) (Abrahamson 2000ba). Their framework defines the levels of success achieved in SPI initiatives.

Agile software development is well-known for its focus on the customer. However, while it has succeeded in developing strong programming, there is an urgent need to understand customer use, perceived value, and shortcomings. Continuous deployment is delivering functional software consistently to customers while learning extemporaneously about customer usage. However, the transition towards short-cycle deployment involves several barriers (Holmstrom et al. 2012). Abrahamson (2000b) suggested five dimensions to gauge the success achieved in SPI: (1) project efficiency, (2) impact on the process user, (3) business success, (4) direct operational success and (5) process improvement fit. These were adapted from the project management literature and support Lean Construction principles.

Some existing implementation theories in construction management advocate "technology push" implementations during which current construction practices need to be radically changed to align with software functionality. Others advocate using well-accepted construction management planning, execution and measuring processes (Hartmann et al. 2012). Mobile Computing Apps appear to be part of the march toward better solutions for practitioners of all industries. Singularly focused individuals can author them and do not have to be integrated with other software modules (Weichbroth, P. 2020)

However, despite this literature, most software programs have been deemed insufficient to meet user requirements. Several comprehensive studies have been conducted to determine usability. The Software Usability Measurement, Inventory (SUMI) survey is specific to answering value-oriented questions. It uses 50-questions making use of five defined subscales for a) Efficiency, b) Affect, c) Helpfulness, d) Control and e) Learnability for querying users' attitudes toward the software. The work on SUMI began in 1986 by Kirakowski, who was entrusted with a project with two objectives: To examine the competence scale of the Computer User Satisfaction Inventory and to achieve an international standardisation database for a new questionnaire.

LEAN CONSTRUCTION SOFTWARE

Toyota's success was no accident. It has been cultivated through high-quality design, unyielding innovation, and bold moves. Their products have met their customer's needs and wants (Womack et al. 2007). Construction Software Developers should adhere to Lean Principles. Seeking perfection is understood as permanent incremental (kaizen) or radical (kaikaku) improvements, eliminating waste and improving value for the client. To achieve perfection, the product and its production process shall be highly specified as content, sequence, timing, and outcome (Spear and Bowen, 1999).

Lean Construction Management (LCM) targets value improvement by eliminating waste. This manifests in less wasted time, better cost performance, and more profit (Fernandez-Solis et al. 2012). Numerous ICT applications have been developed to achieve Lean Production goals in the Construction Industry. Sacks et al. (2010) proposed computer-enabled visualisation to support lean construction by making the whole construction process transparent ("exposing rocks in the lake") called VisiLean, which provides the construction team with a Lean production management system integrated with Building Information Modelling. Another application is KanBIM which supports Lean workflow control on construction sites facilitating short-cycle work planning and monitoring, visualising the age of tasks planned and the status of work in process. Additionally, SetPlan captures information from a BIM model and displays it in a dashboard that supports project participants in developing "one source of truth" for objects as the design unfolds. Ponz-Tienda and colleagues created in 2015, an integrated spreadsheet that computes and visually represents critical information from the Last Planner System for production control. Lastly, SimpLean facilitates the coordination of activities, staff and resources. The software operation mechanism enables the application of Lean Construction concepts, including the Last Planner® System (Dave et al. 2016). Notably, Lean researchers' software development is mostly project focused and does not assist organisational-wide processes such as work acquisition or project portfolio management (Lean Enterprise). A quick search on SCOPUS of the phrase "construction AND project AND software" querying titles, keywords, and abstracts produces 10,995 papers. Contrast that with the words "construction AND software AND organisation or firm or company" results in 5,001 articles. The selected practice featured in this article mainly serves the organisation in the acquisition, planning and execution of the multiple projects they construct each year.

LEAN CONSTRUCTION CONTRACTOR PRACTICES

Stevens and Smolders (2023) listed the following practices as efficacious for construction contracting operations. In this listing, the researcher has added the Lean effect each practice has on productivity.

1. *Dual Overhead Rate Application* – a methodology that precisely assigns overhead (Office G&A) cost to site labour, equipment, material, and subcontractors. This is used in both project estimating and job cost reporting. Accurate costing improves Tender success and flows through to job cost and project return on investment. This reduces wasted work acquisition efforts and gives a project's construction cost.

2. *Job Sizing Adjustment* – adjusting overhead due to the project size variation - the difference from the average job size of the company on average jobs - based on banking and industry data.

Accurate costing improves Tender success and flows through to job cost and project return on investment. This reduces wasted work acquisition efforts.

3. *Predictive Tender Modelling* – a competitive practice that determines a competitor's price from history. It utilises all the factors a constructor uses to adjust their price and systematises the process so the company does not grossly underbid. In other words, using it helps contractors leave less margin between their price and the competitors. Less time predicting and surmising where competitors will price a project and "leaving less money on the table" in a winning bid improves profitability. This reduces wasted work acquisition efforts.

4. *Forecasting Project Resource Demand* – limited and shared inputs such as cash, craftsperson, managers, and equipment must be placed where they produce the most benefit across the projects a constructor will build simultaneously. Forecasting from 6 weeks to 6 months ahead allows executives to ensure share resources are available when needed. In addition, contractors manage multiple projects at a time with limited resources. Therefore, getting more done with the same inputs positively impacts the company and its clients. This reduces wasted resources from quick decisions since planning starts six weeks in advance.

5. *Unit-Based Project Reporting* – utilises a count-based number for all products installed in a building. Units include each for doors or toilets, square meters of concrete forming, cubic meters of concrete or excavation, and linear meters of handrail or coping. This allows precise progress determinations and billing calculations while encouraging quality completion of each unit. A method to estimate, cost and administrate projects more precisely. Less conflict, especially in monthly pay requests. This reduces arguments (wasted time) about physical progress, thus, provides monthly payment justification.

6. *Task Completion Monitoring and Measuring* - all tasks to be completed are listed electronically and assigned to the responsible employee, such as planning or budgeting tasks. Construction firms may allocate many functions to the project manager for the job. Monitoring and measuring completion timeliness increases adherence. Teams build projects. Individual members complete critical tasks such as planning or procuring are best done in a pre-determined order. Accomplishing these tasks ultimately and timely increases multifactor productivity. This reduces wasted time and effort by keeping employees focused on critical tasks.

7. *Staff Load Balancing* – using a dozen or more factors, such as the number of duties, new clients, meetings, and project distance, to determine the relative utilisation of each staff member to ensure a relatively equal workload. People are the enabler of safety, quality, and productivity. Overloaded staff make mistakes; thus, rework negatively affects critical outputs. Employees feigning "overwhelm" is a character problem that should be addressed immediately. This keeps wasted time – underutilisation of some employees and overburdening of others – to a minimum.

8. *Project Site Material Laydown Planning and Logistics* – since approximately 70% of lost time is due to material logistics factors such as delivery timing, counts, product quality and handling, this is a critical practice to improve productivity. Since approximately 70% of lost time is due to material logistics, i.e., timely delivery, counts, quality, and handling, it is critical to pre-plan onsite material storage, handling, and flow. This reduces wasted worker time and effort handling material on the job site.

METHODOLOGY

The paper examines software information to understand the gap between the eight selected practices and the functionality of construction software modules. The user guides were reviewed for vocabulary and functions described in the chosen practices. In addition, the researcher selected a contemporary evaluation framework for software. The researcher decided not to list the specific brands of construction software (user guides) reviewed. This was done for fairness until a more complete and thorough review of the programs can be executed.

The selection of the leading software was executed using two factors: a) the popularity of construction software via an internet search (multiple rankings were considered) and b) industry communication with three experienced executives. This was not meant to be exhaustive or conclusive but a starting point for further research. This paper did not disclose the companies or products due to the nature of the methodology used and the limited data collected.

The selection of practices was determined by consultation with the same executives and the researcher's experience. These eight processes aligned with project operations as well as organisational throughput. More specifically, three were work acquisition, four were project portfolio management, one was project operation, and one was financial management. Generally, these could be considered practices that apply to all sizes and types of construction contractors. Importantly, each practice helps construction firms manage better and stay in business. Stated another way, these practices positively affect a company's risk/reward ratio.
The more mature software developer and contracting firms (existing for 20 years or more) appear to have developed the programming jointly for the flexibility needed. This supports a general perception of the construction executives interviewed and the researcher's experience.

In our research approach, we interview three people with executive-level experience.

- Executive 1 – Construction Contracting Firm Majority Shareholder and Managing Director. They have 20 years of experience in Main Building Work. Clients include national brands, universities and local entrepreneurs.
- Executive 2 – Retired Construction Contractor Firm Owner and Managing Director. Active in academia for an Australian Construction Management Program.
- Executive 3 – A person with over ten years of construction technology selection and implementation for construction contracting firms; still active in the industry but pursuing a PhD in BIM and related strategies.

We asked each executive the following:

- Six demographic questions, such as position and years of experience, and software use, such as weekly hours and discipline focus
- Presented the practice statements and queried for each item its strength - none, low, medium and high
  - The value of the practice
  - The performance of this practice by their firm
  - How strongly is it embedded in the firm's software

RESULTS OF USER GUIDE REVIEW AND EXECUTIVE INTERVIEWS

The results show that none of the eight practices was supported to a significant degree in the surveyed programming modules, as evidenced by the user guides and three knowledgeable industry professionals. However, we did not disclose the names of the software packages for confidentiality and legal considerations.

- Dual Overhead Rate Application - Three Leading Work Acquisition Packages - A supporting function was not found, nor were the executives aware of a software module(s) that offered this.
- Job Sizing Adjustment - Three Leading Work Acquisition Packages - A supporting function was not found, nor were the executives aware of a software module(s) that offered this.

- Predictive Tender Modelling - Three Leading Work Acquisition Packages - A supporting function was not found, nor were the executives aware of a software module(s) that offered this.
- Forecasting of Project Resource Demand - Three Leading Project Operations Management Packages - A supporting function was not found, nor were the executives aware of a software module(s) that offered this. Some packages can capture many variables, compute them and place them in a customer report.
- Unit-Based Progress Reporting - Three Leading Project Operations Management Package - A supporting function was not found, nor were the executives aware of a software module(s) that offered this. Some packages can capture many variables, compute them and place them in a customer report
- Task Completion Monitoring and Measuring - Three Leading Project Operations Management Packages - A supporting function was not found, nor were the executives aware of a software module(s) that offered this. One package can capture many variables, compute them and place them in a customer report.
- Staff Load Balancing - Three Leading Project Operations Management Packages - A supporting function was not found, nor were the executives aware of a software module(s) that offered this.
- Project Site Laydown Planning and Logistics for Material Installation -Three Leading BIM Packages - BIM software can represent this virtually or in print, depending on its the operator must capture the information and master the skills to produce it. However, there is no construction site-operations focus, i.e. 4D is scheduling, 5D is costing, 6D is sustainability, and 7D is facility management.

FUTURE INDUSTRY SURVEY

The researchers have created a survey and will recruit industry professionals. The researchers are applying to our university's Human Ethics committee for approval. The survey

- Asks nine demographic, such as position and years of experience, and software use, such as hours per week and discipline focus.
- Presents the practice statements and queries for each item below in none, low, medium and high
    - The value of the practice
    - The performance of this practice by their firm
    - How strongly is it embedded in the firm's software
- (Asks) What needed practices are not in the software you are familiar with? (text response)
- What mobile computing applications (Apps) are needed? (text response)
- Are any other thoughts you would like to share? (text response)

From this data, the researchers will have evidence of current construction contractor software's general value and utility in work acquisition, project operations, financial management, and building information modelling.

DISCUSSION

Lean Construction asserts that perfection serves the client's wants and needs. Toyota continues to delight its customers with vehicles (and houses) that provide "value for money". In economic recession or growth, the company is focused on perfection. Unfortunately, software developers appear not to have accomplished this goal for construction contractor users.

Software businesses, in general, are economically oriented, like most for-profit organisations. They appear to be falling short of providing high levels of usability and, thus, value. However, mature construction software developers have standardised many unique client requests. Their construction clients seem to have found "workarounds" to perceived gaps. Comments from executives suggested that developers may use construction software programming in other industries under different names. In the short term, this paper asserts that little reprogramming is needed for the construction industry's ICT to support proven practices. They appear to exist primarily in construction companies' authored Excel templates. Hartmann et al. noted (2012) that existing project management best practices guide understanding and supporting BIM implementations at the operational level of an organisation. Also, a group of researchers have advocated for tailoring software to support best practices for over a decade.

Focusing software programming on construction contracting firms' overall operational practices is a slight departure from the project orientation that has been a consistent trend in academia and ICT. This paper asserts that the construction organisation is an enabler of the project outcomes while building other projects simultaneously. Critically, the contracting firm supports the project team, i.e., with office personnel assistance, their experience, coordination of company assets, and enforcing contract terms and conditions. Project teams can be likened to residing on an island where the limits of resources are constrained to the area they occupy. Those in the corporation can connect the project team to capable resources facilitating task completion safer and faster with higher quality. So, systematising company-wide practices with the support of ICT can minimise or eliminate stubborn problems such as efficient resource allocation. Software developers should be incentivised to fill the hypothesised gaps with increased sales.

This paper's selection of effective practices represents critical contractor operational functions – Work Acquisition, Project Operations and Financial Management; not available in one package. Thus, software brands investigated were more than one type. Since the gaps appear consistent across developers and specialised software, there is credible evidence of the gap hypothesised. Importantly, these practices were selected because they generally satisfied the SUMI, SPI and Lean principles.

Some SME contractors rely on customising computer spreadsheets to calculate the supporting information needed to execute some practices. In contrast, others are unaware of the methods or have not taken this additional step. This apparent inconsistent application and execution can be improved by software developers creating interfaces that raise sufficient practice use levels.

Lastly, this previously documented gap in most software (all industries) raises the question, "What else has been overlooked in the programming of construction software now and in the future?" The researcher senses that there is a need for an association-sponsored panel for each construction segment. It might formally report on best practices to enlighten the industry and software developers.

SUMMARY AND CONCLUSIONS

Construction contracting software has the potential to solve the industry's stubborn problems, such as disproportionately high bankruptcy rates and stagnant multifactor productivity. The sources of these issues are many; however, this paper asserts that tailoring construction software to enable effective practices could lessen these problems. This paper documents a review of user guides and informal industry interviews to examine a significant blind spot in the construction industry. Developers have chaotic industry challenges regardless of industry.

The paper hypothesised that a significant gap exists between leading construction software modules and well-accepted practices. This assertion appears credible from interviews and a cursory examination of construction software information catalogues (however, we did not review the working software). Furthermore, the construction software industry seems chaotic and has commercial priorities, such as revenue generation and income diversity. Added to that, mobile computing applications are rapidly filling market voids. Finally, the beginning practices suggested have existed for decades and are considered valuable by many industry professionals showing a blind spot for programming.

ICT researchers have a substantial interest in future possibilities. However, some backfilling seems necessary to make the industry safer, more predictable, reduce costs and produce more value. Of course, realising software's full potential now helps many stakeholders, including workers and contractors, become safer and more efficient while delivering higher quality to society. Also, software firms grow their business. This paper attempts to point toward an alignment of software that can provide value to the industry.

The researcher's future investigation will include interviews and online surveys querying professionals' perceptions of the utility and value of their software and its functionality for supporting the eight selected practices. Specificity, the questionnaire will include brand names and articulated construction processes. A complete exam of product information, including user guides that demonstrate support for the chosen methods, and thus, a more substantial conclusion should be confidently made.

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STRATEGIES FOR THE IMPLEMENTATION OF GREENBIM IN A DEVELOPING COUNTRY

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ABSTRACT

Incorporating BIM and green buildings is a continuous task in the construction industry to achieve sustainable designs and achieve energy efficiency and performance. It entails integrating BIM, building energy performance assessment and sustainable design. Achieving GreenBIM in the construction industry has, however, struggled to achieve this successfully. This study identified the strategies for achieving the implementation of GreenBIM in a developing country context. Data was collected using a well-structured questionnaire from construction industry professionals in South Africa. The collected data were appropriately analysed. It was found that industry leadership, support assistance and promotion of BIM education programmes were the top three strategies for achieving GreenBIM. The study identified and ranked the strategies. This is important for industry stakeholders to achieve the implementation of GreenBIM.

KEYWORDS

BIM, Sustainability, South Africa, sustainable construction, SDG

INTRODUCTION

Most times, humans, through their various activities, ignore the environmental impact. The performance of different activities made by human beings, including a vast role played by the construction industry, has resulted in environmental imbalance. Ofori, (2007) observed that the construction industry impacts heavily on the environment. Construction activities cause excessive resource use, water scarcity, high demand for energy, and environmental pollution in different forms among others (Ametepey & Ansah, 2015; Wieser et al., 2021). For instance, during the lifecycle of a building, it is responsible for +/-37% of the global energy-related CO2 emissions directly and indirectly (Green Building Council South Africa (GBCSA, 2021)). Thus the construction industry products significantly impact the environment. However, the adoption of different measures, including materials, techniques and practices (Ofori, 2007), has been adopted to achieve a lower environmental impact and lately, the adoption of technologies in the construction industry to achieve this goal (Adekunle et al., 2021; Ejohwomu et al., 2021). One of the initiatives in terms of the use of materials to reduce environmental impacts is the

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adoption of green buildings. The green building concept involves the use of different materials and processes throughout the building lifecycle aimed at reducing environmental impact and promote resource efficiency. It therefore contributes to keeping the environment in an environmentally balanced state.

Oguntona et al., (2019) opined that green buildings have outstanding benefits and notable structures compared to regular buildings. Some of the identified benefits of green building include better indoor air quality, protection of the ecosystem, improved energy efficiency, improved health and well-being of building occupants, less maintenance cost, increased marketability, and lower airborne disease transmission, among others(GBCSA, 2021; Oguntona et al., 2019). These benefits affect homeowners, end users, operators and other stakeholders in the construction industry. Parashar & Parashar, (2012) presented a green building as an implementation of constructing a building to be environmentally friendly and resource-efficient throughout the lifecycle of the building. A green building is a building that includes design, development, and operational practices and processes that fundamentally lower the negative effect on the environment. As mentioned earlier, combating the impacts of the environmental effects of the construction industry products and processes also involves the adoption of technology. Building information modelling (BIM) is critical and has a lot of identified benefits for the product, process, and people, among other aspects in the construction industry (Adekunle et al., 2022; Becerik-Gerber & Rice, 2010; Okereke et al., 2021). The combination of these two births the GreenBuilding information modelling (GreenBIM/GBIM) concept.

The implementation and benefits of green building and Building Information Modelling (GBIM) have significantly been recognised in the construction industry(Cassino et al., 2010). GreenBIM involves using BIM tools to achieve improved building performance goals and sustainability on a project throughout its lifecycle (Cassino et al., 2010). The adoption of BIM on green projects enhances the achievement of the project objectives throughout its lifecycle. The implementation of Green Building Information Modelling assists in improving and reducing the use of high energy, natural resources, and pollution and enhances end users' comfort and health. The interaction and integration of green building and Building Information Modelling improve and ensure the achievement of green objectives and sustainability outcomes throughout the building lifecycle. The implementation of Green Building Information Modelling is vital in analysing and understanding the sustainability of materials and other building performances during green building projects (Bonenberg & Wei, 2015). This study is aimed at identifying the critical strategies to achieve GreenBIM implementation in the South African construction industry.

The South African construction industry has been observed to be confronting some challenges impeding its efficiency. A critical one especially considering the target of achieving infrastructural development by 2030 (National Planning Commission, 2011) is the construction material challenge being experienced by the industry (Dithebe et al., 2018; Windapo & Cattell, 2013). Achieving the adoption of GreenBIM in the South African construction industry is important to achieve lower resource depletion and improves water efficiency. Furthermore, it contributes to the efforts of achieving sustainability and lean construction in the South African construction industry. One of the principles of lean construction is the reduction of waste (Sacks et al., 2010), which aligns with the benefits of GreenBIM. GreenBIM is a critical factor for achieving sustainability through environmentally sustainable design (Dall'O' et al., 2020). Also, the implementation encourages less waste production among others (GBCSA, 2021). It thus promotes material efficiency in the South African construction industry and sustainability right from the design stage.

STRATEGIES FOR THE IMPLEMENTATION OF GREENBIM

To achieve a reduction in the impact of construction activities and products on the environment, it is important that GreenBIM is implemented. GreenBIM promotes the achievement of the sustainability pillars of environment, economic and social, on both new building projects, refurbishment or major maintenance operations (Maltese et al., 2017). Various studies have identified some strategies for achieving GreenBIM implementation in the construction industry. A quick look into existing literature suggests that most studies have looked at the strategies to implement green building and BIM separately, but only a few have focused on GreenBIM. Hence most times, the strategies are derived from separate studies for achieving GreenBIM.

The McGraw-Hill report (Cassino et al., 2010) opined that to achieve GreenBIM implementation, there must be a seamless integration of software. According to the report, many software in use is not able to achieve this. Another factor identified by the study is the development of modelling standards towards achieving GreenBIM implementation. (Shukra & Zhou, 2021) opined that there must be an improved capacity in the functionality of BIM software for achieving the green building aspects.

The use of incentives as a strategy to achieve green building was critically examined by Olubunmi et al., (2016). Through a literature review, the study classified incentives into internal and external and examined them from the different stakeholders' perspectives. Similarly, Ebekozien et al., (2022), through a literature review, identified the development of policies as a strategy for achieving green building practices. These identified factors can also be applicable to the achievement of GreenBIM in the construction industry.

For construction industry professionals, there is a need to develop the required skills and expertise required to implement GreenBIM. Like other innovations adopted in the construction industry, there is a need to develop the required skills and competencies (Aliu, Aghimien, Aigbavboa, Ebekozien, et al., 2022). Required competencies for implementation are critical to the diffusion of new technologies and innovations in the construction industry. One critical aspect of the strategies for this study is that they are similar to those required for the implementation of Building information modelling.

RESEARCH METHODOLOGY

The study aims to identify the critical strategies required for implementing GreenBIM in the South African construction industry. A quantitative approach was adopted to achieve this, whereby a well-structured questionnaire was randomly administered to industry professionals online (background information on the professionals are provided under the findings). The research instrument was divided into two sections to collect data on the respondents' background (section A), and the other section (Section B) concentrated on the respondents perspective on the study focus. The section B of the research instrument was designed with the respondents showing their level of agreement from a five-point Likert scale for each of the presented ten strategies for GreenBIM implementation. The questionnaire presented respondents with ten strategies, and they were requested to rank the strategies on a five-point significance Likert scale. This approach has been shown to be effective in collecting data on different subjects in the construction industry and understanding professionals perspectives (Aliu, Aghimien, Aigbavboa, Oke, et al., 2022; Oladiran & Onatayo, 2019) and in studies involving emerging technological trends in the construction industry (Adekunle et al., 2022; Akinradewo et al., 2022; Ikuabe et al., 2022). A total of sixty-four responses were retriefved for the study.

To establish the reliability of the measurement instrument, a reliability test was conducted using the Cronbach’s Alpha. A value of 0.996 was achieved. This is considered a good value in light of the 0.7 minimum requirements for reliability (Kaiser, 1974; Pallant, 2010). Other tests conducted on the collected data include the mean, standard deviation and the Kruskal-Wallis test.

FINDINGS

BACKGROUND INFORMATION OF RESPONDENTS

The respondents for the study consist of sixty percent holders of a bachelor's degree, twenty percent of the respondents hold a diploma, 9.2% of the respondents have a Masters degree, this is followed by 7.7% possessing a Matric certificate, and 1.5% are PhD holders. The profession of the respondents comprises 33.8% Quantity surveyors, 21.5% construction managers, 16.9% electrical engineers, and 12.3% of the respondents are civil engineers. Other professions in the respondents are Architects (7.7%), Mechanical engineers (3.1%), safety managers and town planners (1.5% respectively). Respondents possess various degrees of industry experience; most of the respondents have between 0 – 5 years (67.7%). Other respondents possess 5-10 years of experience (26.2%), 15-20 years (3.1%) and 1.5% possess experience above 20 years in the construction industry. Furthermore, the respondents predominantly work with contracting organisations (32.3%), followed by those working with government parastatals (27.7%), 20% work with private organisations/clients, and 18.5% are consultants. The heterogeneity observed in the demography reveal the respondent are suitable for the survey.

STRATEGIES FOR IMPLEMENTING GREENBIM

Table 1 shows the respondents ranking of the strategies to implement green BIM in the South African construction industry. Based on the responses from the respondents, industry leadership was ranked first with (MIS=3.66; SD=1.250), support assistance from construction industry stakeholders was ranked second with (MIS=3.64; SD=1.252), quality of GreenBIM Model was ranked third with (MIS=3.63; SD=1.291), promote Green BIM educational programmes (MIS=3.63; SD=1.303) was ranked fourth, develop Green BIM training (MIS=3.63; SD=1.374) were ranked fifth, national standards was ranked sixth with (MIS=3.63; SD=1.202), business changes was ranked seventh with (MIS=3.58; SD=1.206), green BIM legal contracts was ranked eighth with (MIS=3.56; SD=1.296), government support was ranked ninth with (MIS=3.53; SD=1.272) and project procurement systems - integrated project delivery was ranked tenth with (MIS=3.52; SD=1.345).

Table 1: Strategies for GreenBIM implementation

Strategies	Mean	Std. Deviation	Ranking
Industry leadership	3.66	1.250	1
Support assistance from construction industry stakeholders	3.64	1.252	2
National standards	3.63	1.202	3
Quality of Building Information Modelling Model	3.63	1.291	4
Promote Building Information Modelling educational programmes	3.63	1.303	5
Develop Building Information Modelling training	3.63	1.374	6
Business Case	3.58	1.206	7
Building Information Modelling Legal contracts	3.56	1.296	8
Government support	3.53	1.272	9
Integrated project delivery	3.52	1.345	10

Table 2 presents the Kruskal-Wallis H statistics, where it was tested if there is a significant difference in the response based on the professional classification. It is observed that there is no significant difference in the responses except for "integrated project delivery" where the value achieved is 0.02. This is lower than the 0.05 established as the significant level (Pallant, 2010). Similarly, this was tested for the categories of respondents based on their familiarity with the GBIM concept, and it was revealed that there was no significant difference in the responses. It thus means respondents perceive the strategies similarly, irrespective of their familiarity with the GBIM concept.

Table 2: KW statistics of responses

	Professionals		**Familiarity with GBIM**	
	Kruskal-Wallis H	Asymp. Sig.	Kruskal-Wallis H	Asymp. Sig.
Government support	2.309	0.315	1.225	0.874
Industry leadership	0.277	0.871	2.717	0.606
Business Case	0.634	0.728	0.973	0.914
National standards	3.196	0.202	1.360	0.851
Develop Building Information Modelling training	1.829	0.401	3.070	0.546
Promote Building Information Modelling educational programmes	4.963	0.084	2.420	0.659
Integrated project delivery	7.800	0.020	3.242	0.518
Quality of Building Information Modelling Model	2.438	0.296	1.592	0.810
Building Information Modelling Legal contracts	2.613	0.271	1.994	0.737
Support assistance from construction industry stakeholders	1.814	0.404	2.368	0.668

DISCUSSION

The result suggests that there must be industry leadership to achieve GreenBIM implementation. This has been observed to be the case in most countries regarding BIM implementation (Edirisinghe & London, 2015; Smith, 2014). Although leadership can be provided by the government or other stakeholders, in some cases, a hybrid approach was adopted. It is, however, worth noting that the strategy adopted is often times tailored to the context and the prevailing factors (Adekunle et al., 2022).

Another result worthy of note is that respondents ranked integrated project delivery low. Cassino et al., (2010) identified integrated design and software integration as critical components for achieving GreenBIM. However, the promotion of BIM training for industry professionals and integrating BIM into educational curriculums are considered very critical to achieving GreenBIM implementation in the South African construction industry. There is a need to develop standards and frameworks to support the implementation of GreenBIM in the South African industry. Additionally, GreenBIM training frameworks to achieve the technical competencies required must also be developed. It thus implies that for GreenBIM to be adopted, all stakeholders must be actively involved and play significant roles.

The results also underscore the digital transformation of the construction industry specifically the adoption of BIM. The benefits, impacts and value of BIM implementation in the construction industry has been extensively researched (Adekunle et al., 2022; Akintola et al., 2016; Becerik-Gerber & Rice, 2010; Dakhil & Alshawi, 2014; Mostafa et al., 2018; Seyis, 2019). These studies has established the importance of BIM to the construction industry.

However, a critical aspect which has rather been given less attention but which is considered important to the implementation of GBIM is the quality of the BIM model. Considering the vital role of BIM in the impmentaion of GBIM, the quality of model geberated is considered critical in achieving GBIM. Thus there must be high level impelemtation of quality assurance process to ensure that BIM models produced are of meets the required industry standards.

CONCLUSION

This study identified the critical strategies for the implementation of GreenBIM in the construction industry. It revealed that to achieve GreenBIM implementation; there must be industry leadership; this might be undertaken and provided by the government. However, considering the respondents' response, there is a need to create awareness and practical benefits of GreenBIM for the South African construction industry to be done. Various professional bodies and private sustainability champion groups must embark upon this. However, there is a need for policy development to support the implementation and provide the legal framework. Therefore, GreenBIM leadership must be provided by a hybrid approach whereby the government and other stakeholders play different but intentional roles to achieve an industry-level GreenBIM adoption. This is imperative to achieve sustainability goals and promote lean principles of waste reduction, especially from an industry that contributes heavily to the environment. The strategies identified are important to achieving sustainability in the construction industry. It should be noted that this study was conducted in the South African construction industry context; however, the findings can be improved on by other researchers. Also, the findings can be adopted by other developing countries with similar contextual variables. In addition, the variables adopted in the study are majorly related to existing BIM studies as thereis a dearth on GBIM studies in the study area. Further research can be conducted on the assessment of the maturity of GreenBIM in developing countries and the framework for achieving industry-wide diffusion.

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BUILDING INFORMATION MODELLING (BIM) FOR PROJECT PLANNING: MEASURES TO IMPROVE ITS ADOPTION

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ABSTRACT

The Architecture Engineering and Construction Industry (AEC) uses Building Information Modelling (BIM) to simplify and enhance sustainability in construction projects. The industry experiences difficulties in achieving project success globally and nationally due to insufficient planning. Technology is required to address this issue by incorporating it into the project planning phase. Therefore, BIM is considered the necessary tool to bridge this gap. This research aims to examine the advantages of implementing BIM during the project planning stage of construction projects. To gather data, a quantitative research approach was employed, and professionals in the South African built environment were surveyed using a questionnaire. The data collected were analysed using descriptive and inferential analysis. Findings from the analysis discovered that the top three measures to improve BIM implementation for project planning in the construction industry are competitive advantage, cost and time savings, and collaboration among AEC professionals. The research concluded that these measures could encourage the adoption of BIM among construction professionals in South Africa.

KEYWORDS

BIM, built environment, collaboration, management, project planning.

INTRODUCTION

Various authors such as Adekunle et al. (2022a), Demirkesen & Ozorhon (2017) and Akinradewo et al., (2021), had submitted that professionals in the AEC community are not accustomed to collaboration. Sakikhales & Stravoravdis, (2017) noted that this is the case even in the early stages of a project. During the project planning stage, architects, engineers, and contractors work individually which eventually leads to double handling of some activities. Requests for Information (RFI), stagnation of work as drawings gets finalised, plant hired not being utilised all adds to the cost of a project (Azmy, 2012). Innovative technologies such as building information modelling (BIM) which has been adjudged to be effective in construction project management can be useful in this regard (Akinradewo et al., 2022). Although, Wang &

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Chien (2014) discovered that BIM is widely used for visualisation and simulation of construction project. However, countries like the United Kingdom (Gledson, 2016) and United Arab Emirates (Mehran, 2016) are benefitting from BIM usage heavily due to its implementation in the early stages of the construction project. This saw BIM moving away from being a visualisation and simulation software to being used as a design and project planning tool.

Traditionally, each member in the construction industry looks out for their best interest (Hardin and McCool, 2015). The incentive for the assessment of BIM in project planning provides the building blocks which may provoke unification of AEC members. Technology is constantly evolving through updates and BIM is no different (Migilinskas, et al., 2013). Sakikhales & Stravoravdis (2017) stated that to effectively use BIM, it must be implemented in the early stages of the project life cycle. Project initiation and planning are regarded as the most crucial stages in a project life cycle by the authors, and they further explain the importance of integrating agile project management during these phases to realise profound results of ensuring quality is met during the planning phases. According to the Project Management Institution, a project life cycle has five stages (Akinradewo et al., 2022a). These five stages are project initiation, followed by project planning, followed by project execution, followed by project monitoring and control, and the last stage is project closure. Furthermore, Hardin and McCool (2015) agreed with this notion and suggest that to fully leverage BIM and its tools, the industry must adopt a modernised and collaborative project delivery method. While there are various studies carried out on BIM usage in the construction industry, majority of these studies focused on the adoption but not specifically on the applicable stages of its adoption. This research work presents a novel contribution to the field of construction by evaluating measures to improve the implementation of BIM in the project planning phase of construction projects. This research has not been carried out before in the research study area being a developing country with limited capacity to fully adopt BIM for construction projects. This is envisaged to help promote the awareness of BIM and how it is useful in achieving construction projects to time, cost, quality in an efficient manner.

BIM FOR CONSTRUCTION PROJECT PLANNING

The spread of an innovation, such as BIM, is dependent on methods to increase its growth after its initial acceptance. Implementing BIM necessitates a technical dramatic transformation in both developed and poor countries (Migilinskas, et al., 2013). Almost every step of the planning and design process can now be done digitally, with data being transferred and shared in a standardized digital format. Recent years have seen an increase in the proportion of data handled by BIM software. BIM is revolutionizing the AEC and the way buildings are built (Turka & Klincb, 2017). In a bid to promote the implementation of an innovation, Olarewaju & Ibrahim, (2020) outlined a requirement for positive and constructive policies as the driving force behind the construction industry due to the possibility for improved economic growth in their study. Adoption of BIM necessitates strategy, therefore, planning and coordination needs the use of these tactics. The challenges associated with design management and project delivery, as pointed out by Senthilkumar and Varghese (2013), have led to the adoption of BIM. BIM challenges existing methods like on-site modifications, project delivery approaches, and lack of standardization. BIM promotes the use of standardized “objects” and pre-fabrication, as noted by Davies et al. (2015). During the design stage, BIM transfers power upstream and reduces variation on the construction site, leading to a more uniform outcome. Altering the project managers traditional role in the process (Sakikhales & Stravoravdis, 2017).

According to Wibowo (2009) and supported by Adekunle et al. (2022b), the construction industry’s economic importance stems from the fact that it benefits multiple parties involved, resulting in a snowball effect that contributes to overall economic growth. Hence, Odubiyi et al. (2019) discovered that embracing BIM within the parties involved in the supply chain is key factor in stimulating the acceptance of BIM in the industry. Akinradewo et al. (2022b) highlighted that the public sector is the largest client for the construction industry in any given country. As Wong et al. (2010), Smith (2014), and Davies et al. (2015) noted, governments in countries such as the USA, UK, and Scandinavia can mandate the use of BIM to increase its adoption. Additionally, the private sector plays a vital role in creating new business techniques and opportunities (Akinradewo et al., 2021). Therefore, a collaborative effort between the public and private sectors, as proposed by Odubiyi et al. (2019), could promote greater adoption of BIM. Although Building Information Modeling (BIM) Level 2 has been widely adopted, there are still some indications that SMEs are slow to adopt the technology. Because of the delay in adoption, small and medium-sized enterprises (SMEs) in the public sector now face a competitive disadvantage (Awwad, et al., 2020).

Smith (2014) outlines that the possibility of BIM success is more likely when the client drives the implementation. NBS, (2020) reported a lack of customer demand being the most prevalent hurdle in the implementation of BIM. The report further stated that the client plays a substantial role in data management environment, associated with BIM. This prompts the need for more research since the available research does not focus on how to incentivise the client. According to Windapo and Cattell (2013), the construction sector contributes to economic growth, job creation, innovation, and business opportunities while enhancing the quality of life for its customers.

To operationalise the identified measures to the improve the implementation of BIM for Project Planning, Table 1 highlights the identified variables and their sources. These articles were extracted from SCOPUS database using the following keywords: "BIM" AND "Project Planning", "BIM" AND "Project Management", and "BIM" AND :Planning". This search yielded 47 documents but only 42 were accessible and therefore adopted for this study.

Table 1: Identified variables for measures to improve the implementation of BIM for Project Planning

S/N	Measures to Improve	Authors
1.	Policy	Sibiya, Aigbavboa, Thwala, (2015); Olarewaju & Ibrahim, (2020)
2.	Agile Project Management	Senthilkumar & Varghese (2013), Davies et al. (2015); Sakikhales & Stravoravdis, (2017)
3.	BIM Requirements for construction supply chain	Wibowo, (2009); Odubiyi et al. (2019)
4.	Government Intervention	Gerbert et al. (2016); Davies et al. (2015)
5.	Private Sector Intervention	Succar (2009); Odubiyi et al. (2019)
6.	Increase BIM Awareness	Froise & Shakantu, (2014)
7.	Subsidies for SME's	Awwad, Shibani & Ghostin, (2020); NBS, (2020)
8.	Client Incentivisation	Smith, (2014); NBS, (2020); Windapo & Cattell, (2013)
9.	Adoption of BIM standards	Awwad, Shibani & Ghostin, (2020)

RESEARCH METHODOLOGY

The objective of this study was to contribute to the existing knowledge on the effective implementation of BIM in the early planning stages of construction projects, using a quantitative research methodology. Quantitative research is useful for gathering data from a significant population and providing numerical measurements of specific aspects of phenomena. The study surveyed quantity surveyors, project managers, engineers, construction managers, and architects in the Gauteng province of South Africa using a pre-designed questionnaire with a 5-point Likert scale in two sections. The first section extracted information about the respondents' demographics in which three questions were asked. The second section focused on the identified latent variables to measure the benefits. In total, four questions were asked in the close-ended questionnaire. The choice of Gauteng province was because it houses the majority of the professionals within the country who are adopting modern technologies for construction activities. 189 questionnaires were randomly distributed to professionals within the study area between September and November 2022, and 167 questionnaires were recovered totalling 83% response rate. All the questionnaires recovered were deemed to be suitable after being reviewed for completion. The Mean Item Score (MIS), Standard Deviation (SD), and Exploratory Factor Analysis (EFA) were used to analyze the data obtained from the questionnaire. The reliability coefficient of the data collection instrument was determined using Cronbach's alpha, with a cutoff alpha of 0.70. The analysis revealed a coefficient of 0.91, indicating high reliability of the retrieved data.

FINDINGS AND DISCUSSION

According to the findings from the analysis conducted, majority of the respondents work at a consultancy firm with the data indicating a total of 48% while professionals working with contracting firm are 28% of the population sample. Also, tertiary students and government employees both make up 12% each. The most common qualification among respondents was the bachelor's degree (32%). In second place were Bachelor Honour's degree (28%) and Diploma (28%). Highest qualification possessed by the respondents was the master's degree (12%). An overwhelming majority of the respondents have worked for 0-3 years (60%), this indicates that the population sample is quite young in the industry, followed by 4-8years of experience (28%) while 8% of the sample has 9-15 years of experience. Only 4% of the respondents have worked for more than 15 years. This is an indication that the respondents possess above average knowledge to provide tangible answers to the research question.

Table 2 captures measures to improve the implementation of BIM for project planning in accordance with the opinion of the respondents. The highest ranked measure is Training workshops for BIM (MIS= 4.48, SD= 0.823), followed by Introduction of faster hardware and software (MIS= 4.32, SD= 0.802), in third there is tie between top management support (MIS= 4.28, SD= 1.208), and Increase BIM awareness (MIS= 4.28, SD= 1.137), in fifth the need to make BIM more user friendly (MIS= 4.20, SD= 0.913), was expressed by the respondents. The last five ranks are occupied by Shift to a collaborative project delivery method (MIS= 3.80, SD= 1.118), Adoption of BIM standards (MIS= 3.88, SD= 1.269), Client Incentivisation (MIS= 3.68, SD= 1.376), Subsidies for SME's (MIS= 3.60, SD= 1.323), and Altering project management role (MIS= 3.12, SD= 1.364) respectively.

Table 2: Ranking result of measures to improve the implementation of BIM for project planning

Measures	Mean Item Score	Std. Deviation	Rank
Training workshops for BIM	4.48	0.823	1
Introduction of faster hardware and software	4.32	.0802	2
Top management support	4.28	1.208	3
Increase BIM awareness	4.28	1.137	3

Make BIM more user friendly	4.20	0.913	5
Introducing Policy that encourage BIM usage	4.16	1.106	6
Raising BIM benefits awareness	4.08	1.038	7
Making BIM a mandatory requirement to construction supply chain	3.96	1.172	8
Government Intervention	3.88	1.269	9
Private Sector Intervention	3.88	1.301	10
Shift to a collaborative project delivery method	3.80	1.118	11
Adoption of BIM standards	3.76	1.332	12
Client Incentivization	3.68	1.376	13
Subsidies for SME's	3.60	1.323	14
Altering project management role	3.12	1.364	15

In addition, the collected information underwent exploratory factor analysis to identify how the variables were related based on the participants' opinions. The findings indicated that the KMO measure of sampling adequacy was 0.607, which is an acceptable value for conducting factor analysis since it is greater than 0.6. Bartlett's test of sphericity also produced 0.000 significant value, indicating the degree of multivariate normality of the distribution set. The total variance of the measures to improve the implementation of BIM for project planning revealed four components which had eigen value of above 1 namely (5.238, 2.429, 1.601, and 1.424). The components eigen value defined the 34.922%, 16.193%, 10.677%, and 9.496% respectively of the variance which indicates 71.288% of the total variance of the data set. The requirement that the combined proportion of variance in the extracted components should be 50% has been met, indicating that the four sets of factors can sufficiently represent the views of experts in South Africa. The research employed PCA-based factor grouping and direct oblimin rotation. Table 3 presents the pattern matrix which highlights how the factors have been clustered together.

Table 3: Exploratory factor analysis pattern matrix for measures to improve BIM implementation for project planning

	Component			
	1	**2**	**3**	**4**
Client Incentivization	0.859			
Subsidies for SME's	0.664			
Private Sector Intervention	0.557			
Government Intervention		0.867		
Top management support		0.805		
Making BIM a mandatory requirement to construction supply chain		0.776		
Training workshops for BIM		0.680		
Raising BIM benefits awareness		0.500		
The need for faster hardware and software			0.919	
Make BIM more user friendly			0.888	

Increase BIM awareness		0.539	
Introducing Policy that encourage BIM usage		0.491	
Altering project management role			0.821
Shift to a collaborative project delivery method			0.775
Adoption of BIM standards			0.617
KMO Value			0.607
Bartlett's TOS result	Chi-Square value		197.772
	Degree of freedom		105
	Sig.		0.000

Based on the opinion of the respondents, the clusters were named thus.

Component 1: Economic Stimulus Measures. BIM can help businesses and governments save money and be more productive by facilitating the timely completion of projects. As a result, the construction and technology industries stand to grow, and more people will find employment as a result.

Component 2: Implementation Initiatives. Efforts to implement BIM software in the building sector are becoming increasingly vital. Through the implementation of cutting-edge technological methods, these endeavours hope to boost teamwork, accelerate workflow, and finalize projects with better results. The construction industry is pushing for the widespread use of building information modelling (BIM) through a combination of government intervention, executive buy-in, mandated requirements, and educational events like workshops.

Component 3: Adoption and Promotion Efforts. The expansion and improvement of the building sector will be impossible without the widespread use of and enthusiasm for Building Information Modelling (BIM). Making BIM more accessible to the general public, spreading the word about its many advantages, and enacting policies that promote its use are all initiatives with the same goal in mind. BIM can significantly boost project outcomes and fuel economic growth by fostering better collaboration and cutting down on inefficiencies.

Component 4: Implementation in Project Delivery Processes. The use of Building Information Modelling (BIM) is critical to the success of today's project delivery methods. Project management is different now than it was before the widespread adoption of BIM standards and the move toward collaborative project delivery. By simulating and visualizing building projects in real time, BIM helps architects, engineers, and contractors head off major problems before they arise, saving valuable time and money.

Notably from the clusters is that some clusters like component 1 are well defined based on the variables that makes up the component, while the other clusters suggest that the needs are systemic and highly interrelated. This is allowed in EFA depending on the responses retrieved from respondents (Osborne & Costello, 2009). The findings of the measures to improve the implementation of BIM aligns with the opinion of authors in the body of knowledge. For instance, Davies et al. (2015) opined that it is widely regarded that government involvement is a key measure to improve the implementation of new technologies. Consequently, the findings of this study also ranked government intervention highly. Similarly, Odubiyi, et al., (2019) identified that making BIM a mandatory requirement to construction supply chain, will aid in the uptake of the software which also aligns with the findings of this study. Even though integrated project delivery method was identified as integral to the usage of BIM for project planning, respondents ranked it as the one least measure to increase BIM uptake for project planning. These findings are suggesting the need for education for BIM because most of the highly ranked measures are related to an investment into R&D. To increase awareness, people either have to see or hear about it. Respondents unequivocally agree that training workshops are an important measure to the implementation of BIM. Hence, education is key to ensure the longevity of BIM. Prominent companies, stand to gain the most from BIM for project planning as reported by Gledson, (2016) and Wang & Chien, (2014) who stated that BIM is more mature as a pre-construction design tool. However, as the biggest client, the government's involvement is required as well.

CONCLUSIONS

BIM is a technology that is getting much popularity among professionals in the construction industry. BIM enhances collaboration, planning, design, and project management. However, the widespread adoption of BIM is a challenging process, as it requires the industry to standardize its practices and information. Consequently, the support and involvement of both the public and private sectors are crucial to the success of BIM. The government, as the construction industry's biggest client, has a pivotal role in promoting the adoption of BIM, while the private sector drives its advancement by developing innovative business practices and opportunities. This study aims to evaluate measures to improve the implementation of BIM in the project planning phase of construction projects. The study used a quantitative research approach, employing a questionnaire survey to collect data. The data was analyzed using both descriptive and inferential analysis. The findings from the analysis revealed that training workshops, improved hardware and software, and top management support are the primary measures to enhance BIM's adoption for project planning. Based on the respondents' opinions, the study identified four main components of measures: Economic Stimulus Measures, Implementation Initiatives, Adoption and Promotion Efforts, and Implementation in Project Delivery Processes. The study concludes that there is a consensus on the importance of various measures to improve BIM's implementation in the construction industry. The findings align with previous studies emphasizing the importance of education and investment in research and development to promote BIM's usage. The study recommends that the government must be involved in promoting BIM's adoption, and professionals in the industry must be engaged in workshops and training. The study is limited to professionals in the Gauteng province of South Africa, and further research is required to get a more general opinion from professionals across South Africa.

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BARRIERS TO THE ADOPTION OF BUILDING INFORMATION MODELING IN QUANTITY SURVEYING PRACTICE IN SOUTH AFRICA

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ABSTRACT

One of the occupations in the construction sector is quantity surveying (QS). This duty is essential to the accomplishment of a construction project since it decides whether it will be finished on schedule, on budget, and to the requisite standard. The practice has received several criticisms for failing to correctly carry out her duties. Adoption of contemporary technology like Building Information Modeling (BIM) in its practice has become necessary to eliminate mistakes, inaccuracies, and omissions. However, South African QS practitioners face challenges in implementing BIM. Hence, this study seeks to examine these challenges. A survey approach was utilised. Ninety (90) of the one hundred and fifteen (115) questionnaires that were distributed to quantity surveyors in Guateng Province, SA were returned and considered appropriate for analysis Kruskal-Wallis, percentage, mean item score, and standard deviation were used to analyse the collected data. The results indicate that the main obstacles to the adoption of BIM in QS practice are a lack of BIM competence, a lack of government enforcement, opposition to change, and a lack of client demand for BIM. This study therefore suggests that BIM trainings be given top priority and that the government take the initiative in promoting BIM adoption throughout the nation, especially for public projects.

KEYWORDS

BIM Adoption, Barriers, Profession, Quantity Surveying, South Africa.

INTRODUCTION

The quantity surveying profession is one the construction professions, who’s most common duties are to measure the quantity of materials as well as the workmanship required to get a construction work done (ASAQS, 2018). In order to establish an accurate estimate for construction work that would be utilised in the tendering processes that are necessary before any construction work can commence on a building site, the quantities of materials and labour needed to perform a task were measured. However, more responsibilities have been added to the roles of quantity surveyors as a result of the profession's evolution, including estimation for each of the six construction stages, advice and a plan for the client to ensure the best service and value of the product that the client is paying for, as well as recommendations on which

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contractor to choose, evaluation of the tender documents, Bill of Quantities pricing, valuations of the work completed and the work still in progress (Salleh et al.,2020). Despite these added responsibilities, quantity surveyors are still making use of the traditional procedures of quantifying and pricing even to this day, which are very time consuming and can give inaccurate figures most of the time (Olsen & Taylor, 2017). These have led to quantity surveyors failing to get the accurate figures when making a construction cost estimates due to the fact that they deal with a lot of unmanageable numbers being quantities as well as rates, while using the traditional method of quantifying and also preparing the bills of quantities. Hence, the profession has received a lot of criticisms due to inaccurate figures which at times leads to cost overrun of projects. As a result, the need for a technological tool capable of taking a lot of burden off the shoulders of quantity surveying professionals.

The Building Information Modelling (BIM) has been working its way into the construction industry. BIM is a novel technology that has been brought to the planning of building structures, their construction, and their digital administration (Raphael & Priyanka, 2014). BIM is a type of computer software that allows building structures to be digitally shown and all necessary digital activities to be taken before any physical construction work can begin. According to Boeykens (2018), the BIM is a tool or model that is used to share, collaborate, and coordinate the data of a specific building structure in terms of its design, construction, as well as its operation. This tool was created to aid in the transformation and advancement of the construction sector. BIM has advanced from 2D drawing to 5D presentation, object modeling, and analysis, making it easier for construction professionals, including quantity surveyors, to execute high-quality work (Boeykens, 2018). Hence, construction professionals are forced to evolve with this technological advancement or run the risk of being left behind. Considering the need to reduce errors, inaccuracies and omissions in the taking-off quantities and estimations of the building costs, and the need for improvement in the delivery of accuracy in quantifications and fast quantification and estimation processes in the South African construction sector, it is important the BIM tool is adopted by the quantity surveying professionals as it would lead to improvement in delivery of their services to the clients of the industry.

According to Odubuyi et al (2019), the total construction sector must develop in order to benefit the shareholders or investors in the sector, hence it is essential that quantity surveyors perform their tasks and responsibilities better. The use of BIM is one innovation that can revolutionise the construction industry and is the best strategy to advance the field (Odubuyi et al, 2019). The usage of BIM makes it possible for the quantity surveyors and the entire project team to have access to the data necessary for performing their tasks (Harrison & Thurnell, 2015), while also managing excellently the information that is included in it (Usman et al, 2015). Furthermore, Alhasan et al (2017) posited that every stakeholder or member of the project team wants to see an increase in project productivity. This can be achieved through efficient communication, automated data input, automatic taking-off of quantities, and improved cost estimates capability of BIM. There are several other benefits of BIM to quantity surveying practice that have been identified in existing literature. However, the move to adopt BIM in South Africa's private and public sector (client side) and amongst different building professionals (Quantity Surveyors, Architects, Civil Engineers, and Mechanical & Electrical Engineers etc.) has been very slow. The reason for this has been attributed to several factors. For example, Makenya & Ally (2018) opined that the slow uptake of BIM adoption might be due to lack of BIM expertise, while Criminale & Langar (2017) attributed it to resistance to change by the various professionals within the industry. Thus, the aim of this study is to examine the barriers to the adoption of BIM in quantity surveying practice in the South African construction industry. The conclusions will be useful in identifying the militating factors. An evaluation of the barriers as they were noted in the literature is presented in the following section. Following are the research techniques used and the findings of the study. The results are then discussed, and conclusions are then presented.

THE QUANTITY SURVEYING PRACTICES AND BIM

The primary responsibility of a quantity surveyor is to make sure that resources are used appropriately in the construction sector. They are also in charge of monitoring the project's finances and provide cost consulting services to the customer during the whole building process (Raphael & priyanka, 2014). A quantity surveyor's other crucial responsibilities include measuring construction projects and creating bills of quantities, or BOQs (Olatunji et al., 2010). A quantity surveyor's duties include providing advice on procurements, budgeting for construction costs, measuring on-site, organizing the schedule of work, preparing the final accounts, keeping track of expenses throughout the project, and negotiating tenders (Kottathara & Gunavel, 2017). Since quantity surveyors are the most crucial individuals in the construction sector, it is crucial that they carry out their responsibilities correctly and to the best of their abilities. However, when they carry out their duties, quantity surveyors frequently encounter difficulties that cause them to make mistakes in their job, such as errors in the movement or arrangement of data between their files, errors in numbers, duplications, and omissions of certain crucial data (Kottathara & Gunavel, 2017).

BIM makes it possible for those working in the architectural, engineering, and construction fields to plan, design, build, and manage building facilities in an efficient and effective manner (Rakib et al, 2019). Before the advent of BIM, building information was displayed using 2D drawings, making it challenging to understand the dimensions and specifications given. Later, Computer Aided Design (CAD) was introduced, allowing architects to view building plans digitally. This was followed by the development of 3Ds, which provided the realistic digital drawings of buildings (Lorek, 2018). The project's programming and scheduling of the data are integrated with the information from the 3D model in the 4D, which also monitors each action that is undertaken. The 5D then connects the previously mentioned information with the information cost, such as the quantities and prices or rates (Smith, 2007). Even if most quantity surveyors are unsure about it, the implementation of the BIM in a building project may help them increase the efficiency of the job they undertake (Fung et al., 2014). For instance, the usage of BIM can enhance and automate the present quantity surveying methods, such as taking off quantities from the construction drawings that have been created by the architects (Beukes, 2012). This reduces the amount of time required to quantify and estimate using the conventional approach, which South African quantity surveyors have always understood and continue to use. The ability of BIM to extract quantities from 3D designs and create bills of quantities simultaneously has helped reduce the amount of time spent on the building process, which is why BIM has been lauded as a huge technical advancement ever since it was first introduced (Olatunji et al., 2010).

BARRIERS TO THE ADOPTION OF BUILDING INFORMATION MODELING IN QUANTITY SURVEYING PRACTICE

LACK OF BIM EXPERTISE

The lack of competent individuals in building information modeling precludes most construction firms' quantity surveyors from implementing BIM in the majority of their procedures (Makenya & Ally, 2018). Chan et al. (2019) also highlighted that it is challenging for BIM to be incorporated in the quantity surveying operations due to the lack of available experienced and qualified professionals who have worked on BIM before.

LACK OF AWARENESS

According to Makenya & Ally (2018), there are low levels of knowledge about the implementation of BIM, which means that many individuals are unaware of how BIM may assist them in carrying out their jobs as quantity surveyors. In addition, the study by Criminale & Langar (2017) also mentions the fact that some individuals are not actually aware of BIM, despite the fact that there are not many of them, and on the other hand, others are aware of it but lack sufficient knowledge of it and how it functions.

RESISTANCE TO CHANGE

According to Harisson & Thurnel (2015) and Aibinu & Venkatesh (2015), quantity surveyors are so accustomed to carrying out the majority of their tasks in a conventional manner that they don't appear particularly eager to change their way of doing things. According to Criminale & Langar (2017), the interest in adopting BIM is hampered by the absence of corporate motivation to convert to building information modeling, which is often demonstrated by company leaders. This resistance to change behaviour is also brought on by the fact that the business is highly accustomed to carrying out tasks in a certain method, which makes them reluctant to adapt to the BIM procedures.

SCARCITY IN BIM TRAINING AND EDUCATION

According to Makenya & Ally's (2018) and Smith (2007), the majority of quantity surveyors do not utilize BIM mostly due to a lack of BIM training. The adoption and application of BIM by quantity surveyors are hampered by a lack of training programs that may facilitate the transfer of knowledge and skills (Chan et al, 2019). Another significant obstacle to the widespread usage of BIM technology is a lack of training for users on how to operate it. Organisations don't invest in staff training because they believe it to be time- and money-consuming (Criminale & Langar, 2017).

LACK OF KNOWLEDGE OF THE BUSINESS VALUE OF BIM

Makenya & Ally (2018) opined that one of the barriers to the adoption of BIM in quantity surveying operations was the lack of knowledge about the benefits that BIM may provide to these organisations. Another significant barrier to quantity surveyors adopting BIM is a lack of information or comprehension of the return on investments (ROI) brought on by its utilization (Haupt & Hefer, 2016). Another reason for BIM's delayed adoption and lack of acceptance is the challenges associated with monitoring or evaluating its effects on the project (Chan et al, 2019). The other businesses are prevented from adopting BIM technology and understanding the commercial value that BIM models convey because they are unaware of the financial benefits that are achieved by using BIM models (Criminale & Langar, 2017).

SOFTWARE COMPLEXITY

It is highly discouraging for quantity surveyors to accept the usage of BIM in the everyday services they give due to the complexity of the software (Haupt & Hefer, 2016). Criminale & Langar (2017) noted that the complexity of BIM, which prevents many professionals or construction teams from using it to execute their jobs, is one of the obstacles to its acceptance in quantity surveying techniques.

ADDITIONAL COSTS IN BIM TRAINING

Quantity surveyors in particular will need to receive BIM training, which will incur fees that most employers or business owners will be compelled to pay but most of them are unwilling to do so (Makenya & Ally, 2018). Because of this, most organisations' quantity surveyors are unaware of BIM and how it might help them with their everyday tasks (Horrison & Thurnell, 2015). Although it is also believed that the owners of the organizations investing in BIM may be a fantastic move owing to the advantages that are connected to the adoption and implementation of BIM.

Other barriers to the adoption of building information modeling in quantity surveying practice as obtained from review of existing literature can be found in Table 1 below.

RESEARCH METHODOLOGY

The study examined the barriers to the adoption of building information modeling in quantity surveying practice in South Africa. The study deployed a quantitative approach through questionnaires use as instrument for data collection. This approach was utilised due to the possibility of covering a large pool of respondents with the aid of research questionnaire (Tan, 2011). Gauteng Province of South Africa was the study area and the respondents targeted for the research were Quantity Surveyors. Relevant literature were reviewed for this study and information related to the objective of the study were obtained and used for the design of the research instrument, which is a structured questionnaire. The questionnaire had two sections, with the respondents' demographic information elicited in the first section. While the respondents' perspective on the barriers to the adoption of building information modeling in quantity surveying practice were elicited in the second section of the questionnaire. The libertarian scale of 1 (strongly disagree) to 5 (strongly agree) was used to rate the questions presented to the respondents. A total number of ninety (90) of the one hundred and fifteen (115) questionnaires that were distributed to quantity surveyors in Guateng Province, SA were returned and considered appropriate for analysis. Kruskal-Wallis as adopted by Otasowie & Oke (2022), percentage, mean item score, and standard deviation were used to analyse the collected data. In addition, the Cronbach's alpha reliability test was conducted for the purpose of determining the reliability of the data set and a value of 0.932, which represents a high consistency level.

FINDINGS AND DISCUSSION

The background information of the respondents revealed that 22% of the respondents has Diploma, 52% had a bachelor's degree, another 22% had an Honours degree, and 4% had a master's degree. Furthermore, 49% of the sample assessed was Contractor Quantity Surveyors, 14% were Professional Quantity Surveyors, 5% were Candidate Quantity Surveyors, and 32% were Junior Quantity surveyors. In addition, 36% of the respondents had ten (10) to fifteen (15) years of experience, 29% of the respondents had five (5) to ten (10) years of experience, and 35% had less than five years of experience as quantity surveyors in the construction industry. Finally, 58% of the respondents work for the contracting firms, 22% work for government, and 20% work for consulting firms. These findings suggest that the study's target respondents, who were quantity surveyors, were fairly represented and that they had a sufficient degree of education to comprehend the study's questions (Otasowie & Oke, 2022).

Table 1 below shows the barriers to the adoption of building information modeling in quantity surveying practice in South Africa in a ranked order from the highest mean to the lowest mean. It can be observed that barriers with the same mean were ranked based on their Standard Deviation (SD) from the mean. A scenario in which most data are close to the mean is represented by a small SD, while a large SD shows that the data point is widely apart from the mean (Field, 2005). Hence the barrier with the same mean were ranked based on this. The mean of each barrier is the average of the responses obtained from each respondent.

The results show lack of BIM expertise as the highest ranked barrier (MIS=4.22, SD = 0.86). This was closely followed by lack of government enforcement (MIS=4.20, SD = 0.88); Resistance to change (MIS=4.13, SD = 0.93); lack of knowledge of BIM value (MIS=4.02, SD = 1.09); no client demand for BIM (MIS=4.00, SD = 0.91); high initial cost of BIM (MIS=4.00, SD = 0.97); additional costs in BIM training (MIS=3.98, SD = 0.92); lack of support from company's executives (MIS=3.93, SD = 0.91); scarcity in BIM training (MIS=3.89, SD = 0.95).

Table 1: Barriers to the adoption of building information modeling in quantity surveying practice in South Africa

Barriers	Rank	MEAN	SD
Lack of BIM expertise	1	4.22	0.861
Lack of government enforcement	2	4.20	0.877
Resistance to change	3	4.13	0.933
Lack of knowledge of BIM value	4	4.02	1.090
No client demand for BIM	5	4,00	0.911
High initial cost of BIM	6	4.00	0.971
Additional costs in BIM training	7	3.98	0.921
Lack of support from company's executives	8	3.93	0.908
Scarcity in BIM training	9	3.89	0.945
Lack of BIM standards in construction	10	3.85	0.899
Lack of IT infrastructure	11	3.85	1.172
Scarcity in BIM education	12	3.83	0.986
Issues with skills transformation	13	3.72	1.089
Increased client cost	14	3.70	1.127
Lack of amendments in forms of contract	15	3.69	0.865
Lack of awareness	16	3.59	1.141
Software complexity	17	3.56	0.925
Changes in the duties of quantity surveyors	18	3.50	1.005
Difficulties using BIM	19	3.43	1.143
Threat to the QS	20	3.39	1.172
Technical risks	21	3.31	1.146

The research's findings corroborate a study by Makenya & Ally (2018) that found that most construction firms' quantity surveyors are not adopting the usage of BIM in their regular quantity surveying operations since there aren't enough competent individuals in building information modeling. The study concurs with a study by Chan et al. (2019) that found it challenging for quantity surveying practices to embrace BIM due to a lack of more seasoned and knowledgeable workers that have expertise with it. The study goes on to further concur with a study by Harrison & Thurnel (2015) that found there was insufficient government enforcement of policies that would have allowed the BIM to be included into the tasks performed by the design, construction, and engineering industries. It acknowledges that the absence of government initiative to adopt and use BIM is impeding and limiting its application in projects. Makenya & Ally (2018) agreed with this as well. Furthermore, according to Harrison & Thurnel (2015), whose study the present study confirms, opined that quantity surveyors are so accustomed to carrying out the majority of their tasks in the traditional manner that they don't even appear to be open to change in their working style. The findings of this study further corroborates that of Criminale & Langar's (2017), that the interest in adopting BIM is hampered by the lack of corporate willingness to convert to building information modeling.

In order to compare respondents' perspectives based on their years of experience, a Kruskal-Wallis test was conducted. It was shown that the mean values for the barriers to the adoption of building information modeling in quantity surveying practice in South Africa do not differ significantly. From the P-values in Table 2, it can be deduced that both entry level and experienced quantity surveyors that were the respondents for this study all responded and ranked the identified barriers similarly.

Table 2: Kruskal-Wallis Test Showing P-Values for Barriers to the adoption of building information modeling in quantity surveying practice in South Africa

Barriers	P-Values
Lack of BIM expertise	0.053
Lack of government enforcement	0.057
Resistance to change	0.053
Lack of knowledge of BIM value	0.090
No client demand for BIM	0.051
High initial cost of BIM	0.072
Additional costs in BIM training	0.081
Lack of support from company's executives	0.058
Scarcity in BIM training	0.054
Lack of BIM standards in construction	0.091
Lack of IT infrastructure	0.075
Scarcity in BIM education	0.086
Issues with skills transformation	0.079
Increased client cost	0.067
Lack of amendments in forms of contract	0.062
Lack of awareness	0.641
Software complexity	0.058
Changes in the duties of quantity surveyors	0.065
Difficulties using BIM	0.073
Threat to the QS	0.072
Technical risks	0.066

CONCLUSION

This study evaluated the barriers to the adoption of building information modeling in quantity surveying practice in South Africa. Relevant literature were reviewed for this study from which barriers to the adoption of building information modeling in quantity surveying practice were identified. The findings of the study show that lack of BIM expertise is the most significant barrier to the adoption of building information modeling in quantity surveying practice. Furthermore, the findings of the study revealed other barriers to include lack of awareness, lack of amendments in forms of contracts lack of BIM standards in construction, lack of government enforcements, lack of IT infrastructure, lack of support from the company's executives, lack of knowledge of BIM value, resistance to change, scarcity in BIM training, software complexity, additional costs in BIM training, high initial costs of BIM, changes in the duties of quantity surveyors, no client demand for BIM. These findings suggest the need for the government to make the use of BIM compulsory in construction projects in South Africa. This will in turn make quantity surveyors in the country to embark on BIM related trainings to improve their awareness and knowledge of the technology. Furthermore, there is the need to make provision for the training of quantity surveyors on BIM technology in the country to increase profitability, and improve the efficiency of quantity surveyors for greater cost certainty/ improve the cost estimation. In addition, by holding seminars, more quantity surveyors would be made aware of what BIM is all about. In order to consistently add value and improve their professional services, quantity surveyors must constantly reinvent themselves. Finally, although the current study provides insights into significant barrier to the adoption of building information modeling in quantity surveying practice, the study was conducted in the Gauteng Province of South Africa, which could be a limitation. Hence, similar studies should be conducted in other provinces within the country.

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APPLICATION OF BIG DATA AND INTERNET OF THINGS IN THE BUILT ENVIRONMENT: A BIBLIOMETRIC REVIEW

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ABSTRACT

Using big data and internet of things (IoT) technologies is without a doubt growing more and more important on a global basis. The two 4IR components stand out for their innovative methods that might aid organizations in developing high-performing teams and a culture that is performance-focused. Big data platforms offer methods for methodically eliminating data from data arrays that are too intricate to be used in standard data-processing applications. The Internet of Things and big data are used in every sector. The utilization of big data is significantly growing on a global scale. A staggering number of individuals, including architects, contractors, suppliers, and clients, are now involved in the building process. Large data warehouses are mined for information using big data analysis techniques, which then make the information available to all parties involved. With an overview of IoT and big data applications in the built environment, this research aims to tie current trends to them. In order to identify prior studies on IoT and big data in the construction industry, this study did a bibliometric evaluation and looked at the SCOPUS database. In addition, this probe only allowed recovery of documents from the previous 16 months. Papers based on quantitative, qualitative, and literary reviews made up the majority of the contents. The research also revealed that the bulk of articles were published in industrialized countries. Construction is under underway on phases that will largely focus on IoT research as well as an audit and assessment of the expansion of big data applications. The essay also evaluates and discusses recent advancements in the internet of things and big data industries. Data management, storage systems, automation, and retrofitting are the four main clusters of big data and IoT applications, according to the report. It has been shown that there are several potential when big data and IoT are combined. When properly implemented, such solutions provide professionals and other industry participants in the building sector an accuracy of over 90%.

KEYWORDS

Adoption, Industry 4.0, Big data, Internet of Things, Trend

INTRODUCTION

The desire to increase construction productivity is driven by the sector's well-known inefficiency in transforming raw resources into commodities and by the significance of

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building or infrastructure development to economic growth (Hussain & Al-Turjman, 2021). Modern building techniques make use of cutting-edge digital technologies to improve building operations. Building project planning and execution are being revolutionized by the internet of things (IoT), big data, and cyber-physical systems (Bilal et al., 2016). Evidence suggests that the construction industry's transition to Industry 4.0 will require the integration of cutting-edge technologies like Big Data and the Internet of Things in order to automate value-added jobs and data-acquisition systems (IoT). IoT refers to a network of physical objects that are embedded with sensors, software, and other technologies for the purpose of connecting and exchanging data with other devices and systems over the internet and big data is data that contains more variety, arrives in greater volumes, and moves more quickly (Yin & Kaynak, 2015; Patel & Patel, 2016). The application of big data and IoT is then a thorough procedure that removes inaccurate information from construction operations, improving quality and efficiency, lowering costs, and increasing value for the client. Many Internet of Things (IoT) devices operate on remote servers that may be accessed via the cloud, however clients occasionally employ big data processing to speed up data transit (Hassanalieragh et al., 2015). This model enables more immediate outcomes for time-sensitive procedures by retaining power to analyze some data locally. The bulk of the Internet of Things (IoT) focuses on the instant analysis and utilization of incoming data, big data tools can help with some other crucial tasks including predictive analytics. Predictive analysis takes into account machine performance and service alerts over time, and then builds the library of data required to foresee impending issues (Sayad et al., 2019). Due to this, construction businesses can maintain their equipment proactively and prevent the potentially expensive downtime that comes with equipment breakdown.

Furthermore, users may monitor vital information about their cars through the Internet of Things, often known as telematics, such as idle speed, tire pressure, and GPS tracking (Gamil et al., 2020). Additionally, it increases productivity, helps employees visualize tasks and solve problems, and may be used to provide instructions for on-the-job responsibilities. Additionally, it promotes worker and workplace safety. Funding for the design and development of new technologies will increase as more people become aware of the potential and requirements of the Internet of Things (Gbadamosi et al., 2019). When it comes to what this kind of technology is capable of, the sky is the limit. Since they are designed to use automated systems to handle things like heating, cooling, and lighting, smart buildings are becoming more and more prevalent (Chen et al., 2022). Routine maintenance might be aided by smart buildings, which can also look for potential system issues. They are lauded for having little environmental effect and for assisting in lowering energy waste (Zhao et al., 2022). The building process could be hastened while preserving worker safety when new technologies are developed (Lawal & Rafsanjani, 2022). Big data and drones are two cutting-edge technologies that might be utilized to analyze and create a building design more quickly. Despite the Internet of Things' (IoT) sluggish adoption in the construction industry, many increasingly understand that adopting cutting-edge technology into operational strategies is essential for construction businesses to remain competitive.

As technology advances, the quantity of data in the world today only gets more and more overwhelming (Bilal et al., 2016). The construction sector now manages petabytes (1015 bytes) of data. The industry makes extensive use of data from several disciplines throughout the life cycle of a facility. Building Information Modelling (BIM) is a process for methodically collecting three-dimensional CAD data to promote multidisciplinary collaboration among stakeholders (Munawar et al., 2022). BIM data is frequently networked in a variety of distinct formats; it is typically geometrically stored in three dimensions, computationally expensive (using graphics and Boolean operations), and compressed. This scattered data is merged to produce federated BIM models, which are continuously produced and kept long after a facility has reached the end of its useful life (Teisserenc & Sepasgozar, 2021). The design data for a five-story building model may eventually be 80GB in size, demonstrating how rapidly BIM files may grow (Lin et al., 2016). No matter how they are presented, it is clear that the success of the industry is greatly influenced by these facts. The spectrum of Big BIM Data sources has expanded due to the introduction of embedded devices and sensors, which have caused facilities to start producing vast volumes of data both during and after construction. Due to the extensive collection of BIM data, the construction industry has entered the "Big Data age" (Su et al., 2021). Due to its enormous size (terabytes, petabytes, and beyond) and diversity (a wide range of heterogeneous formats, including text, sensors, audio, video, graphs, and more), big data stands out (rapid streams of the data). The generation of data serves as an example for all three aspects of big data. A huge, fascinating, and dynamic collection of construction data is usual. Due to the massive volumes of design data and timelines, construction data is vast (Moeini et al., 2017). The use of big data and the Internet of Things to improve building practices and lessen negative impacts has been covered thus far in this article. The connection between big data applications and IoT in the context of the built environment has not been extensively studied. The major goal of the study is to understand how big data and IoT applications connect to recent advancements in the built environment.

IOT AND BIG DATA APPLICATION

When construction companies effectively use technology to solve typical workplace difficulties and improve operations, they benefit from improved productivity and better response to the industry's growing requirements (Arai & Morimoto, 2021). Construction companies are exploring integrating IoT and big data for a number of reasons, including sluggish productivity, declining margins, increasing schedule overruns, and rising competition (D'Amico et al., 2020). The categories stated in Table 1 are what are driving the use of IoT and big data in the construction industry.

Table 1: Application of IoT and Big data

IoT and Big data application areas	Motivation	Reference
Productivity	The construction sector is governed by deadlines and goals. Because they force budget increases, backlogs must be prevented at all costs. IoT can increase readiness and efficiency, which will increase output.	(Opoku et al., 2021); (Aghimien et al., 2020); (Adekunle, Aigbavboa, Akinradewo, et al., 2022)
Maintenance	Real-time data is now available, making it feasible to arrange maintenance breaks or refueling as well as turn off idle equipment and determine the status of any asset.	(Zhang, 2020); (Dave et al., 2016)
Safety and Security	Any material or item theft may be easily prevented with IoT connected tags since these sensors will inform you of the whereabouts of the materials or item at all times. Sending a human worker to undertake a comprehensive check is no longer necessary.	(Awolusi et al., 2019); (Demirkesen & Tezel, 2022)
Unmanned aerial vehicles and Autonomous vehicles	Key construction equipment has to be manually tracked since it takes time and is prone to mistake. The installation and usage of unmanned aerial vehicles and autonomous vehicle on these significant assets has many advantages for the construction/project management. These vehicles can perform operation autonomously in areas where human interventions can be risky and dangerous.	(Gao et al., 2020); (Hacker, 2017)

BIM optimization and Digital twins	In addition to providing an ever-growing dataset that can be integrated with machine learning to perform predictive analytics, to monitor active job sites, a combination of historical data from prior jobs and the ongoing stream of real-time data from IoT sensors may be employed. This will make construction even smarter.	(Hmidah et al., 2022); (Jiang et al., 2021)
Data Mining	Waste management, BIM-based quality control in construction engineering, and other significant areas of the construction industry have all made use of data mining. For the purpose of making decisions on construction management projects, data mining finds relevant patterns and information. As it combines and analyzes various construction items into homogeneous groups, cluster analysis is a crucial data mining technique for the construction industry.	(Sacks et al., 2009); (Munawar et al., 2022)
Sensors	There are several types of sensors that may operate in a certain environment and be applied to improve management effectiveness by setting up and sending out alarms. They can be employed to find a number of alarming circumstances that demand rapid response. Humidity, temperature, and pressure calculations may be tracked by linked and monitored equipment utilizing IoT software and processes. This will notify management to any possible risk that needs rapid care.	(Heiskanen, 2017); (Andújar-Montoya et al., 2017)
Real-Time Site Map	Employers may use this technology to both identify workers on the job and prevent them from entering dangerous areas. Using this, a real-time map of the building site could be created so that everyone could see who is working where and when. If the situation is actually dire, some danger zones and managers' only zones can be highlighted on the map, and other individuals may be persuaded to stay away from such areas if they are not absolutely necessary. All of this data may be gathered by IoT devices on the internet and used for projects.	(Sharma et al., 2020); (Abu Ghazaleh & Zabadi, 2020)

RESEARCH METHODOLOGY

An exhaustive and thorough audit of big data and IoT in construction was achieved using a descriptive research method and bibliometric evaluation of the literature. According to Hallinger & Kovaevi (2019), a quantitative analysis of bibliographic data that categorizes research articles, authors, and themes provides a comprehensive view of a study field. The bibliometric review employs a variety of qualitative indicators to evaluate the current level of study on a certain subject utilizing a wealth of bibliographical data (Baas et al., 2020). Since content analysis enables one to generate logical conclusions from literature obtained from a database, the bibliometric evaluation was deemed appropriate for the study project that it was implemented into (Garrigos-Simon et al., 2019). The database to be utilized for the research study was chosen in the first phase to ensure that a sizable amount of literature could be acquired. Due of the popularity and effectiveness of Web of Science (WoS), ScienceDirect, and SCOPUS, we originally looked at these sources (Singh et al., 2021; Charoenthammachoke et al., 2020; Martn-Martn et al., 2018). The software utilized for this study can only examine data from one database at a time, even if it is possible that all three databases were used. SCOPUS was chosen following a preliminary search of all databases since it had a greater number of articles published and was found to have more comprehensive coverage, with the majority of publications on WoS and ScienceDirect also being indexed on SCOPUS. The search was limited to works published in 2019 and 2022 using words that includes “Big data”, “Applications”, “Internet of Things”, and “Building Sector” or “Construction sectors”. Table 1.0 contains papers from the top ten journals in order to achieve the study's objectives, the top 10 journals was derived based on the numbers of article published. Journal articles were preferred to book chapters and conference papers because the judgments and analyses that go into them are typically more thorough and in-depth. When these keywords were used to search through the title, abstract, and keywords of published articles, only 81 of the 104 items discovered were relevant to the study's objectives. Journal articles, conference papers, and book chapters make up the 145 items. The bibliometric network visualization tool VOSviewer was used to analyze these texts (Yu et al., 2020). Content analysis was utilized to describe the investigation's findings in order to achieve the study's objectives.

Table 2: Top ten journals explored

Journal	**Number of documents**
Automation in construction	13
Journal of Building Engineering	9
Material and Structures	8
Journal of Construction Engineering and Management	6
Journal of Industrial Information Integration	6
Sustainability	5
Advanced Engineering Informatics	5
Engineering, Construction and Architectural Management	3
Future Generation Computer Systems	3
Engineering structures	3

FINDINGS AND DISCUSSION

This study attempts to summarize the current research goals for internet of things and big data in the construction industry, as was already stated. A quantitative content analysis of the 145 recovered documents was used to achieve this. To do this, a co-occurrence network of terms was created using bibliographic data acquired from retrieved articles. The creator of VOSviewer claims that a minimum of three keywords should be used for keyword co-occurrence analysis (Anna & Mannan, 2020). Thus, among the indexed and author's keywords, our investigation used a minimum of three co-occurrences. Only 78 out of 960 keywords met the co-occurrence criterion; their frequency of recurrence and general strength were confirmed. The internet of things occurred the most in the documents that were retrieved, with a total link strength of 602, showing the magnitude of its involvement in the co-occurrence map (146 times). Given that this survey is focused on the construction sector, the building industry came in second (81 occurrences and 396 total link strength). Big data is the word for the many applications and components of the internet of things and big data, and it is placed seventh out of the remaining 76 terms used in the construction business. The network visualization map of the 78 co-occurring key phrases and their four different clusters is shown in Figure 1.

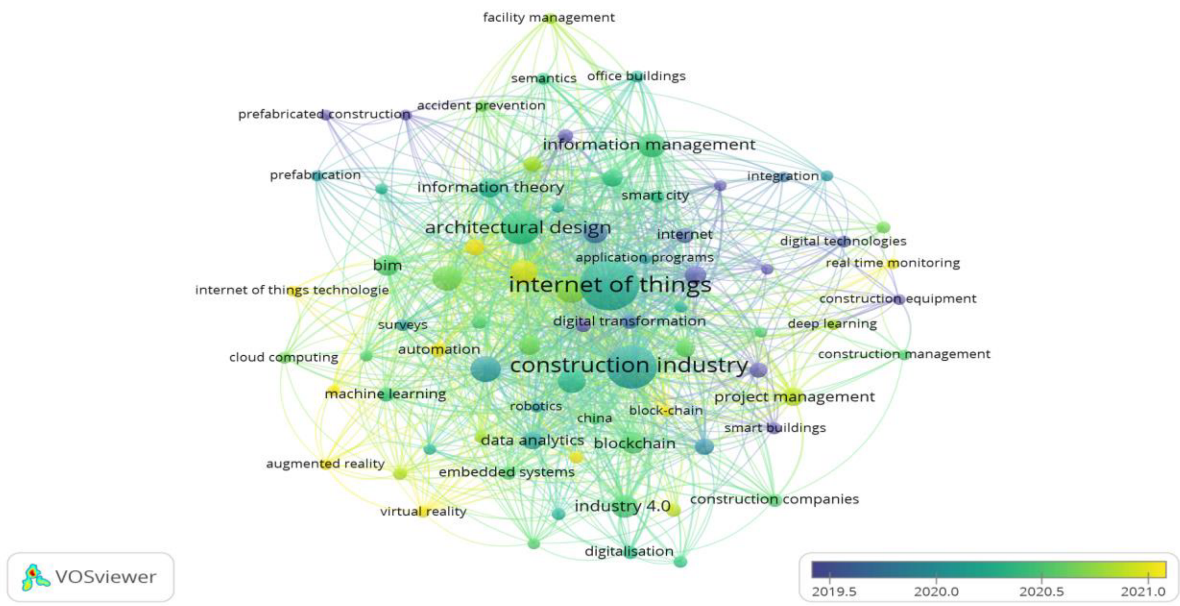

Figure 1: Publication keyword trend overlay visualization map.

Cluster 1 – Storage Systems: On the map, the deep green region with 25 co-occurring phrases represents the Internet of Things area. Construction projects, digital storage, industry 4.0, blockchain, artificial intelligence, embedded systems, and industry 4.0 are notable examples having connections to the core idea ("Internet of things and big data"). Because of this, this cluster may be thought of as a collection of key words for applications connected to the Internet of Things and big data storage. Opoku et al. (2021) claim that IoT technologies may be used to almost any device that can offer important data on its own operation, the success of an endeavor, or even the environmental conditions that we need to remotely monitor and regulate. As a result, they are said to have a wide range of applications.

Cluster 2 – Automating: is the area of light green on the map that has 20 related keywords. Important essential terms include "application programs," "automation," "sensor," "smart city," "digital twins," and others. The utilization of IoT and bid data for the automation of different activities inside the built environment is therefore thought to be the cluster's primary focus. It demonstrates that big data will be able to evaluate massive volumes of data at breakneck speeds, enabling construction companies to focus on the jobsite rather than IT problems (Dave et al., 2016).

Cluster 3 – The purple region on the map with 17 co-occurring terms is Retrofitting. Notable essential concepts include "construction equipment," "deep learning," "integration," "energy usage," "life cycle," and other connotations. Therefore, it is assumed that this cluster is interested in topics pertaining to retrofitting. According to a report by Demirkesen & Tezel (2022), IoT and big data technologies are more useful than ever for the construction industry because of their decreased prices and increased levels of reliability. The digital transition has enhanced productivity across many industries, but the construction industry has been slower to adapt. Building complexity makes things more challenging, but IoT and big data may be able to aid with many issues connected to energy consumption reduction. These strategies might provide businesses a competitive edge despite rising costs.

Cluster 4 – Data management: is the yellow region on the map which has 16 co-occurring keywords. Understanding the underlying concepts of augmented reality, data collection, cloud computing, machine learning, and other related topics is crucial. Therefore, it is expected that this cluster is working on data management issues. Data management's importance has been emphasized in earlier publications. The findings are in line with those of Jiang et al. (2021) and (Adekunle et al., 2022), who explain how the recent expansion of construction big data and the creation of computational tools in the area of information technology enable construction specialists and practitioners to extract and visualize big data for a variety of new applications.

CONCLUSION

Using bibliometric techniques, this study pinpoints areas of construction-related research that prioritize IoT and big data. The study was able to identify the major area of focus in research related to big data and IoT applications inside the built environment based on extracted articles published in the recent sixteen months and indexed in the Scopus database. The results show a rise in the amount of IoT and big data research papers published, with 2021 recording the most papers. This is useful because it highlights the need of having a solid understanding of big data and IoT applications in the built environment as well as the advantages of their adoption for the construction industry. When correctly considered, such technologies provide information to stakeholders and building industry experts that is up to 90% accurate. The paper examines current big data and IoT applications in the construction industry. Big data and IoT have a significant relationship that will only intensify as technology progresses. Construction firms that want to use data effectively should be very selective about the devices used and the data obtained. The process of analytics will be made considerably simpler by making an effort up front to collect only relevant, usable data and by creating internal systems to handle the data in industry-specific ways.

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PROCESS ANALYSIS WITH AN AUTOMATIC MAPPING OF PERFORMANCE FACTORS USING NATURAL LANGUAGE PROCESSING

Svenja Lauble[1], Philipp Zielke[2], Hongrui Chen[3], and Shervin Haghsheno[4]

ABSTRACT

In lean construction projects, much information is collected during the process analysis with the trades. This data is increasingly documented as a reference for use in future construction projects. By doing this, efficient methods are required to use this data. Often, the unstructured naming of data is a challenge for a rule-based allocation of information, and manual work is required to identify the needed data. Therefore, the aim is to develop an automatic mapping of historical performance factors to the tender specifications of a new construction project. To support the process analysis with historical project data, a case study is executed using Natural Language Processing (NLP). With a NLP model, the process descriptions from the tender specifications of the new construction project can be compared with a master database, to filter the right performance factor and calculate the duration for a process. This procedure can be used to support the further process analysis together with the trades to generate a validated construction schedule. The case study shows promising results in the prediction results. First, the mapping quality and second, the prediction accuracy are evaluated. With the developed mapping concept, last planners can validate their estimations of durations in lean construction process planning with a target to support stability in a project. Still, a more detailed description of the processes could increase the prediction results.

KEYWORDS

Digitization, lookahead planning, work structuring, process, complexity.

INTRODUCTION

Regarding the continuous improvement process (CIP) and a well-founded knowledge management system in lean construction projects, companies tend to collect more and more data about their projects. According to a survey by Thomas and Bowman (2022) with 3.916 stakeholder in the construction industry, their data has doubled within three years (from 2019 to 2022). In lean construction projects, much information is documented about the processes. In the Last Planer System and in Takt planning (Haghsheno 2016) a process analysis is done together with the trades as knowledge carriers. A sequence of processes for each product type is compiled here, along with the time and resources required for each process step. This information is increasingly documented as a reference and updated with the real data during project execution. For example, Choo et al. (1998) collect weekly updated data of construction processes using a database called “WorkPlan”. This data is then used to update the weekly work

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planning of the respective project. By documenting the duration of a work package and the manpower behind it, realistic performance factors can be documented (Haghsheno 2016). Figure 1 displays an exemplary database for lean construction projects. In this database, processes are described. With their durations and the manpower available, realistic performance factors can be calculated. A performance factor defines the required calculation time for one unit of a process task with one person. These performance factors, together with the process description, can serve as a master database for the process analysis of a new project (see Haghsheno et al. 2016).

For example, Frandson et al. (2013) define 'gathering information' about the process as the first phase of the Lean method's Takt planning. And, for the Last Planner System, the phase and lookahead planning with the trades can be supported by historical information. Here, the master database can serve as a starting point for planning and as basis for discussions with the construction trades.

Database for Lean Construction projects

Process name	**Duration (D)** (in hours)	**Manpower (M)**	**Units (U)**	**Performance factor (D/M/U)** (hours / unit)	**Comment (e.g. special conditions)**
XXX	8	4	10	0.2	Snow
XXX	6	2	40	0.075	-
…	…	…	…	…	…

Figure 1: Database example for Lean Construction projects.

As a result, unnecessary buffers and capital commitment costs for construction employees and their machines are reduced. Also, time pressure can be prevented by enhancing motivation, security, and quality (Rogel 2013).

With detailed work steps, covering different types of construction, and the existing product complexity in construction, databases can get very complex and large. This is also shown by publicly available databases. E.g., the Construction Cost Information Center for Architects in Germany, called 'BKI' (Baukosteninformationszentrum), is documenting several thousand possible work steps with their average performance factor and costs per process description. Besides complex databases, a mapping to process descriptions of new construction projects can get quickly complex, as often the naming is not standardized. Following a manual mapping of the correct performance factors causes high levels of manual work with the danger of a misallocation. With the prospect of manual effort, a detailed use of master databases in a process analysis can be prevented.

This paper therefore has the target of analyzing how an automatic mapping of performance factors from a master database to the process description of a new construction project can be designed. Figure 2 displays the concept of the automatic mapping with the master database (right) and the process descriptions of a new lean construction project (left). For example, the tender specifications can serve as the basis for the process descriptions. By mapping the processes of the new project with those of the database, a suitable performance factor is identified. Together with the units, a duration for each process can be calculated.

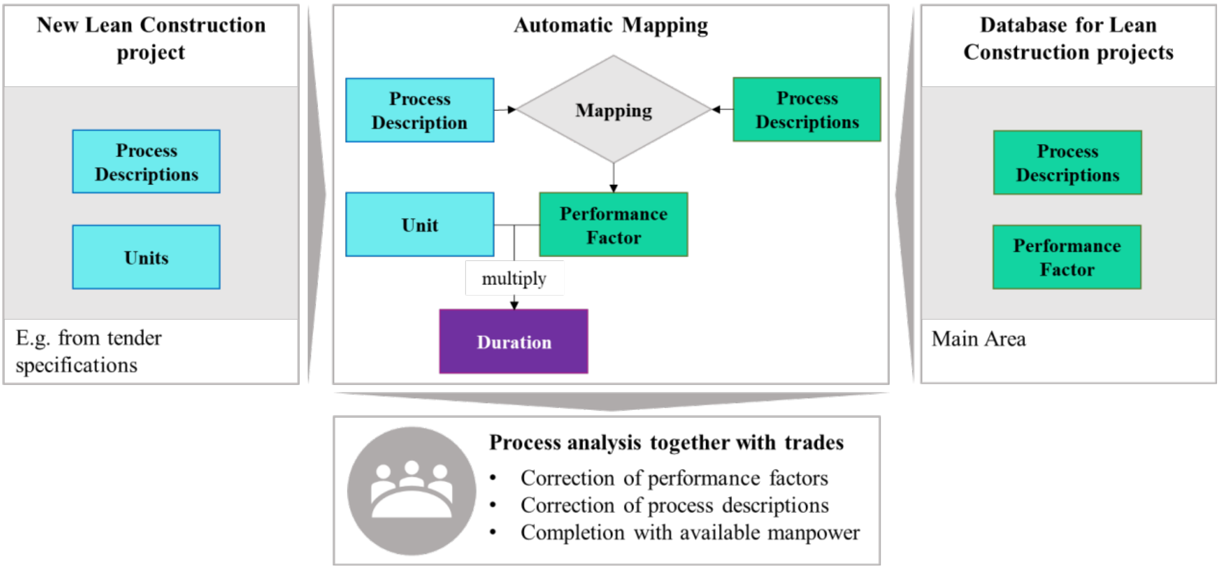

Figure 2: Concept of an automatic mapping of performance factors for a process analysis.

For the automatic mapping, the method of ‘Natural Language Processing’ (NLP) is first described and then evaluated in a case study.

THEORETICAL FOUNDATIONS OF NATURAL LANGUAGE PROCESSING

According to Cambria and White (2014), NLP is a theory-motivated range of computational techniques for the automatic analysis and representation of human language. IBM (Education, 2020) considers NLP to be a branch of Artificial Intelligence (AI). It is concerned with the ability to enable computers to understand text and spoken words in a way that is almost identical to that of humans. Liddy (2001) provided a detailed definition: “NLP is a theoretically motivated range of computational techniques for analyzing and representing naturally occurring texts at one or more levels of linguistic analysis for the purpose of achieving human-like language processing for a range of tasks or applications”. EasyAI (2019) explained NLP concisely and in an easy-to-understand way: “NLP is the bridge that communicates between machine language and human language.” Language is typically unstructured data. NLP is used to let the machine understand and use this information. A consensus can be seen: with the support of NLP, humans can be supported in the lean construction process planning.

So far, NLP has already been part of pilot studies in construction research. Jagannathan et al. (2022) apply NLP to analyze unstructured text data in annual reports of construction contracting companies. Li et al. (2020) use NLP to predict the probability of obtaining construction accident compensation through a practical example in Hong Kong. Wang et al. (2022) develop a virtual assistant with the use of NLP, with whom information retrieval for construction project team members is supported.

According to EasyAI, Deep Learning-based NLP can be divided into three steps: corpus pre-processing, design modeling, and model training. For the pre-processing, the following six tasks can be executed (EasyAI 2019, Bachani 2020):

Tokenization: Tokenization is the breakdown of long texts like sentences, paragraphs, and articles into word-based data structures for subsequent processing and analysis work.

Stemming: Stem extraction is the process of removing the prefixes and suffixes of words to get the root word. Common prefixes and suffixes are “plural of noun”, “progressive”, and “past participle”. For example, “playing” will be converted to “play”.

Lemmatization: Lexical reduction is based on the dictionary and transforms the complex form of a word into its most basic form. For example, “drove” will be converted to “drive”. Each language requires semantic analysis and parts of speech to establish a complete lexicon.

Parts of Speech: In traditional grammar, a part of speech is a category of words that have similar grammatical properties, such as “nouns”, “conjunctions”, and “verbs”.

Named Entity Recognition (NER): NER, also known as “proper name recognition”, refers to the recognition of entities with specific meanings in the text, mainly including names of people, places, institutions, proper names, etc.

Chunking: Chunking is the process of grouping the words in unstructured text and making up phrases.

Easily spoken to design the model, the pre-processed words are used in a **word embedding**. The purpose of word embedding is the vectorization of words. Each word or phrase is mapped to corresponding vectors of real numbers. With these dependencies, words can be allocated. Algorithms such as deep learning can ingest and process these vectors to formulate an understanding of natural language. (Collis, 2017)

Following, the process description of the master database as well as the process description of the new construction project, the data is pre-processed and afterwards vectorized. Hence, the tasks can be compared by their real numbers, and the effort value with the closest match is used as the planning basis for the process analysis. This procedure also serves as the foundation for the methodical approach.

CASE STUDY

METHODICAL APPROACH AND DATA

The methodical approach for the case study, is described in Figure 3. For the case study two datasets are used: the master database and the process description of tender documents from a real-world construction project. First, the mapping quality is evaluated with two indicators, and afterwards, the prediction accuracy for the duration is analyzed.

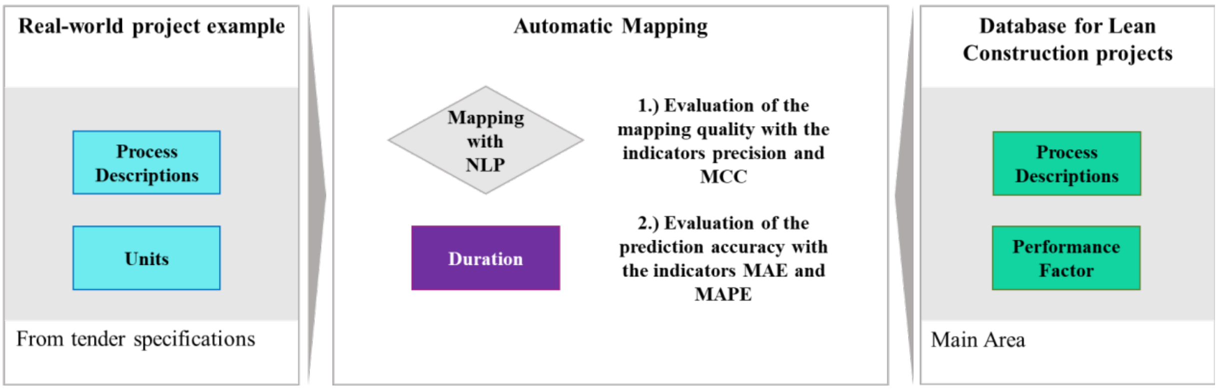

Figure 3: Methodical approach for the case study.

As a master database, the data from BKI is used for the research model. The available dataset contains 3.586 described process steps for new construction projects. The dataset is complete and free of missing data, and its reliability is high. The dataset is available in German and is annually updated. The dataset contains, after removing irrelevant features, six columns with: category type, short task description, long task description, unit, average cost per unit, and performance factor. The mean value of the short task description, text length are 34.29 digits, for the long task description it is 383.06 digits. The mean value is defined as the sum of all digits divided by the number of projects. The performance factor presents the working time in hours, based on one unit. The average performance factor is 1.23 hours with a standard deviation of 9.16 hours, a minimum of 0.01 hours, and a maximum of 260 hours per unit.

The real-world construction project data contains process steps for structural engineering work (earthwork, concrete, and masonry work) described in the tender specifications. In the real-world project data, there is no information about performance factors included. This information is needed to start a well-founded lean construction process plan. The dataset includes 194 entries with a short process description as well as the number of units. To these two columns, the corresponding process description and the performance factor of the master database are manually matched. Entries with no match and null values are deleted. The performance factor is then multiplied by the number of units to calculate the duration. This results in 93 data entries with an average duration of 0.52 hours per unit (performance factor) and 87.60 hours per process step (duration per unit multiplied by the respective unit). Table 1 summarizes the mean and standard deviation for the master database and the real-world project for the performance factors and duration. The performance factors of the real-world project are on average lower than those of the master database and show a lower standard deviation.

Table 1: Description of the data

	Master database	**Real-world project**	
	Performance Factor	**Performance Factor**	**Duration**
Mean	1.23 hours	0.52 hours	87.60 hours
Standard deviation	9.16 hours	0.57 hours	290.06 hours

In the first phase, the master database is prepared with data cleaning process, encoding, and splitting. The data cleaning contains data truncation, data enhancement, and selecting a classification objective:

Data Truncation: Nevertheless, the available dataset of real project consists only of structural engineering work. To control the required resources within the limits of Google Colab and maximize model performance with restricted resources, the master database is limited to the category of structural engineering. After restricting the range, the number of data sets dropped from 3.586 to 1.420.

Data Enhancement: Despite its high quality, the BKI dataset presents a problem for machine learning. In general, to train a classifier, each class always needs multiple data samples for algorithm learning. However, there is only one unique sample to be classified in each class in the current BKI dataset. Therefore, the expansion of the data cannot be avoided, and a replication is performed. In a study, IBM researchers explored different classifiers, and the performances of the classifiers with different numbers of training samples were compared. The results show that the model improves significantly with the inclusion of ten samples (Anaby-Tavor et al., 2019). Therefore, the number of replications of the master database is set to 10. After the data expansion procedure, the number of data points in the dataset increased from 1,420 to 14,200.

Selecting Classification Objective: After filtering the process steps with effort values, there are 14,030 data points left.

Afterwards, the data is encoded. After investigating the duplicate entries, label encoding is used for the short description. Label encoding assigns a number starting from zero to each possible category in the short description column (Yadav 2019). The new dataset includes 14.030 data points and 1.366 category encodings.

In the last step of data preparation, the master dataset will be divided into a training set, a validation set, and a test set. This procedure is known as data splitting. Brownlee (2020) defines data splitting as a technique that is used to evaluate the performance of machine learning algorithms and can be employed in any supervised learning algorithm. The training and test sets were split by 80% and 20%.

After data preparation, the model is developed and various publicly available libraries for Python are utilized: TensorFlow, Transformers, Tune and Scikit-learn. For the model, the framework GBERT is used, which Chan et al. (2020) state the best performing German framework for NLP. The model further on uses several pre-defined hyper-parameters, such as a dropout rate of 0.1, 10 epochs, a batch size of 16, and a learning rate of 2e-5. For the model, the short and the long process descriptions are combined by the separator token “[SEP]”.

After model training, the model will be evaluated by several metrics, such as:

Precision: Precision indicates the proportion of units that the model predicts to be positive and are in fact positive. The mathematical definition is the proportion of the true positives (TP, actual positive and labelled as positive) to the true and false positives (FP, actual negative and labelled as positive).

$$Precision = \frac{TP}{TP + FP}$$

MCC: Matthews Correlation Coefficient (MCC) represents the correlation between the true value and the predicted value. It ranges from -1 to 1. A score of 1 indicates a very good prediction, while a value close to 0 means that the model performs poorly and is like the random classification. The value -1 represents inverse prediction (Grandini et al., 2020). The metric focuses only on whether each class is well predicted, regardless of class imbalance (T, 2021). The formula of MCC with TP, FP, true negatives (TN, actual negative and labelled as negative) and false negatives (FN, actual positive, labelled as negative) is:

$$MCC = \frac{TP * TN - FP * FN}{\sqrt{(TP + FP) * (TP + FN) * (TN + FP) * (TN + FN)}}$$

MAE: To calculate the Mean Absolute Error (MAE) for each known output y and the associated predicted value ŷ, the loss is calculated from Loss (y, ŷ) = |y - ŷ | (Russell and Norvig 2012, Hyndman and Koehler 2006). This metric is characterized by a stronger robustness, and outliers do not affect the result as much. The MAE is calculated with (Sammut and Webb 2010):

$$\boldsymbol{MAE = \frac{\sum_{i=1}^{n} |y_i - \hat{y}_i|}{n}}$$

MAPE: The Mean Absolute Percentage Error (MAPE) serves as an indicator of how good the predicted duration is. The smaller the indicator, the higher the prediction accuracy. The MAPE is the ratio of the difference between the actual output value y and the predicted value ŷ to the actual output value y over all data points (Hyndmann and Koehler 2006).

$$\boldsymbol{MAPE = \frac{100\%}{n} \sum_{i=1}^{n} \left| \frac{y_i - \hat{y}_i}{y_i} \right|}$$

RESULTS OF THE CASE STUDY

To evaluate the performance of the mapping model, itis evaluated with the test dataset from the master database and the real-world dataset. The test dataset of the master database contains

2.806 data entries. The accuracy reaches 0.92. The MCC represents the correlation between the true value and the predicted value. With this metric, it is possible to observe whether each class is well predicted or not. Here, MCC is at 0.92. Overall, the performance of the model on the test set is reasonably positive.

For the real-world dataset, the accuracy reaches 0.65. The value of MCC is 0.64. It is possible to conclude that the model performs less well on the dataset of a real project than on the test set. For both, the metrics are summarized in Table 2.

Still, the matching effort values can be very close, as the assigned tasks can be similar and the matched performance factor is close to the correct one.

Table 2: Overview of the mapping quality

Indicator	**Value**	
	Master database	**Real-World dataset**
Accuracy	0.92	0.65
MCC	0.92	0.64

Therefor the manually mapped durations and the predicted ones are compared for the real-world dataset. As indicators the MAE and MAPE are used as metrics. The MAE is 48.75 hours and the MAPE is 17.63 % (see Table 3).

Table 3: Overview of the prediction results

Indicator	**Value**
MAE	48.75
MAPE	17.63 %

While further analysing these metrics with a histogram shown in Figure 4, there are five mismatches with a difference of more than 50 hours between the predicted and actual duration. The highest mismatch is 2.340 hours, a high outlier. The Q3-quantil shows that 75 % have a difference of 2.5 hours between the predicted and actual value. In 85 % of the mismatches the difference is less than 8 hours or a working day (with 8 hours). The distribution of the prediction errors is displayed in Figure 4.

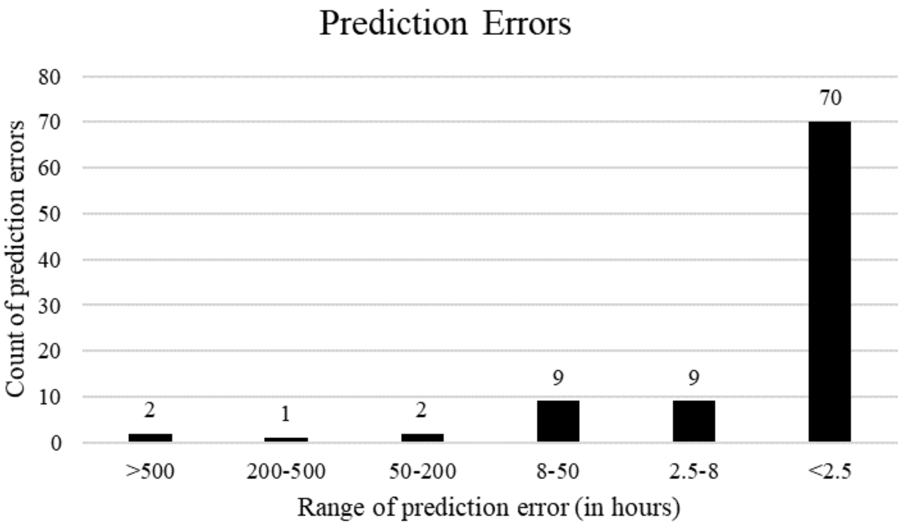

Figure 4: Distribution of Prediction Errors by hours.

Comparing the 2.5 hours in 75 percent of the cases to the 87.60 hours mean duration in the real-world dataset, the overall quality of the prediction is very good. Following, the predicted duration can serve as a basis for further planning. Due to the high deviations with high outliers, an expert must still be included in the scheduling with the target to reduce these outliers and correct the performance factors. These experts can be last planners, as they can validate the predicted durations best with their knowledge and, at the same time, challenge their own estimations.

CONCLUSIONS

In this paper, a concept was evaluated using a master database with historical project data to map the process descriptions to thoseof a new construction project. By doing this, the performance factor of the master database can be multiplied with the number of units of the construction project and a duration as the basis for planning is calculated. As the process description is often not standardized, the method of NLP is used. NLP serves as a bridge between machine language and unstructured human language.

For the concept evaluation, two databases were used. One master database with 3.586 entries describing new construction projects and the tender specifications of a real-world construction project with 194 entries. The mapping quality of the process descriptions between the master data base and the tender specification was 0.65 accuracy and 0.64 MCC. Both indicators show an average to good mapping quality. The higher mapping quality of the test dataset shows the need for a more detailed process description. When further comparing the prediction quality for the duration, the MAPE is 17.63 % and in 75 % of the mismatched cases, the prediction error is smaller than 2.5 hours. This deviation from the 87.60 hours of mean duration is very low, and the concept of mapping performance factors automatically shows its potential. With a first automatic mapping and prediction of the process durations, the time for scheduling can be accelerated and the quality of planning enhanced.

Figure 5 shows the full concept model with recommendations for the construction companies. The master database can be used to map with NLP models process description to the tender specifications of new construction projects. This information can serve as the basis for planning with the trades and their last planners. During the process analysis, performance factors and process descriptions are corrected, and the estimated durations are finalized with the available manpower. The result is a construction schedule that is validated by historical project data. When documenting the performance of the project during its realization, the performance factors can be updated and detailed, and the master database can be enriched by new entries.

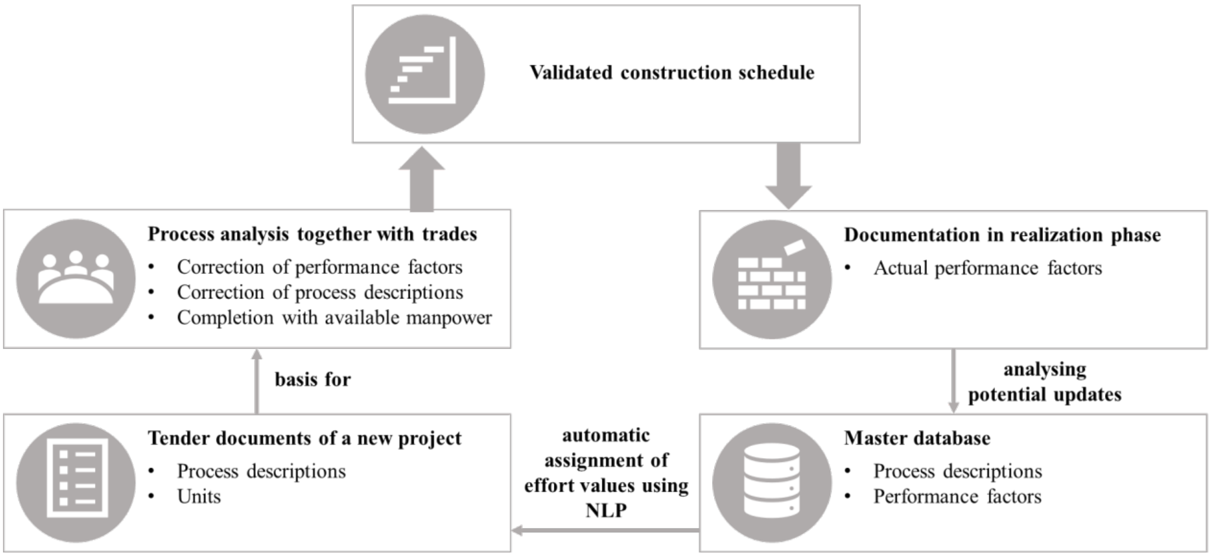

Figure 5: Concept model using NLP to automatically map performance factors to the tender specifications to support the process analysis.

As the case study is performed with one real-world dataset, there needs to be a broader field study using the tender documents of several construction projects. Also, the model acceptance of the schedulers and trades must be evaluated. Here, especially, the allocation of mismatches by the defined model should be analysed with the target of reducing the outliers and strengthening the collaboration between experts and machines.

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PROMOTING THE IPD DELIVERY METHOD IN CONSTRUCTION PROJECTS: A BIM-BASED SMART CONTRACT APPROACH

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ABSTRACT

The adoption of integrated project delivery (IPD) provides several advantages over traditional delivery methods, such as shorter schedules, efficient communication, and higher performance quality. However, its implementation is constantly hindered by many barriers. Existing studies on IPD barriers are limited to quantifying and addressing such obstacles. Additionally, hardly any studies have addressed the potential of advanced technologies in exploiting the adoption of IPD projects. Thus, this study presents an automated system that integrates blockchain, smart contracts, and BIM technologies to facilitate the implementation of IPD projects. Hyperledger Fabric and chaincodes are used to develop the blockchain network in accordance with 4D and 5D BIM models. The developed system simplifies various financial transactions throughout different phases of the IPD project implementation. The system allows non-owner participants to submit requests and review transaction records with the aim of minimizing possible conflicts. The methodology is evaluated by testing it on a real-life case study. The case study is modeled using BIM tools, and the corresponding blockchain network and smart contracts are developed. The findings prove the capability of the developed system to provide a secure and trustworthy platform for managing IPD transactions without the need for third-party involvement.

KEYWORDS

Integrated project delivery (IPD), smart contracts, BIM, blockchain, construction projects.

INTRODUCTION

The integrated project delivery method (IPD) is an innovative delivery method that overcomes many of the limitations of conventional delivery (Ahmed et al., 2021). Conventional delivery methods are characterized by fragmentation (Teng et al., 2019), lengthy processes (Ghassemi & Becerik-Gerber, 2011), and poor information sharing (Rahman & Kumaraswamy, 2004). IPD was introduced to overcome these drawbacks. The IPD system is characterized by early involvement of participants and efficient risk-sharing and compensation systems (Faris Elghaish et al., 2020). Evidence in the literature has shown that IPD has the potential to enhance project performance. For instance, Ahmad et al. (2019) indicated that IPD improves 14 project

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performance indicators, such as cost management, work quality, information sharing, and scheduling management.

However, the adoption of IPD projects always encounters many barriers. Rodrigues and Lindhard (2021) have discovered many barriers to IPD adoption using case-based studies. The found barriers can be summarized as follows: 1) difficulties in estimating the limbs values (components) in various project stages; 2) establishing the culture of having the same control over the project from all participants; 3) the dilemma of having transparency and trustworthiness through the entire project; 4) behavioral barriers as most participants can expect the higher profitability. Similarly, Yee et al. (2017) have categorized all of the barriers into four main categories: contractual barriers, behavioral barriers, structural barriers, and technological barriers. The study concluded that technological barriers are the most critical barriers that hinder the adoption of IPD. To be able to exploit the merits of the IPD system, advanced technology sharing and communication systems are required (Faris Elghaish et al., 2020). Building Information Modeling (BIM) is an example of technology adoption in IPD projects. As mentioned by Salman et al. (2012), BIM can enhance the delivery of projects by providing efficient collaboration between project participants. However, it is argued that integrating advanced technologies, such as blockchain, with BIM can further address many of the IPD barriers (Lamb, 2018).

The latest advances in blockchain technology have presented chaincodes (smart contracts) as an alternative solution that overcomes the downside of the fragmented nature of construction projects (Ahmadisheykhsarmast et al., 2020). Smart contracts are digitalized contractual agreements that provide solutions for the deficiencies in the payment systems of construction projects. Blockchain platforms act as a decentralized and secure system that provides an efficient implementation of smart contracts (Sigalov et al., 2021). It records any transactions or movements of the system on blocks that can be displayed on the ledgers. More on blockchain components will be discussed in the following sections.

To this end, many studies have addressed the potential of blockchain technologies in construction projects. However, the literature lacks the following aspects: 1) the majority of studies presented a conceptualization of the blockchain framework, with no actual implementation; 2) limited studies addressed the integration between IPD and blockchain in the construction industry; 3) potential claims on a construction project are yet to be addressed on the blockchain network. Considering these gaps, this paper presents an integrated system to overcome the obstacles of implementing the IPD method. The objectives can be summarized as follows: 1) identifying and (egorizing the barriers that hinder the adoption of the IPD method in construction projects; 2) studying the potential of advanced technologies (e.g., smart contract and BIM) to overcome some of the identified barriers; 3) developing an automated system that facilities the payment transitions and minimizes possible conflicts, hence promoting the IPD approach; 4) Validating the system by applying the proposed methodology on a real case study. The rest of the paper is structured as follows: the next section provides the literature, followed by the study methodology, which is then validated. Section 4 shows the validation and case study, and section 5 provides the conclusion and recommendations.

LITERATURE REVIEW

IPD is a highly collaborative approach to project management that involves the integration of all stakeholders engaged in a project, including the owner, architect, contractor, and other key team members, within an environment of trust. IPD aims to create a team environment where all parties work together towards a common goal, which is the successful completion of the project. The process begins with the development of a comprehensive project plan, which outlines the scope, schedule, and budget of the project. The project plan is then used to guide the team throughout the project, with recurring updates and revisions made as necessary. One of the key features of IPD is the use of BIM, which helps identify potential conflicts and design issues early in the project, preventing costly delays and rework (Ashcraft, 2011). This section provides a literature review on the barriers associated with IPD adoptions, the potential of BIM, blockchain, and smart contracts in construction projects, and a discussion on which blockchain platforms to be used in the current study.

BARRIERS TO IPD ADOPTION IN CONSTRUCTION

Many studies were carried out to identify and categorize IPD barriers. For instance, Sherif and Abotaleb (2023) classified the barriers of IPD adoption into five main categories. Their study indicated that the majority of construction projects in established and developing countries face technological challenges, such as integration issues between BIM and IPD and unreliable payment systems, which are well-known obstacles to IPD adoption (Durdyev et al., 2019). Further, the adoption of IPD projects requires a high level of information sharing, efficient communication technologies, and reliable payment mechanisms (F. Elghaish et al., 2020). IPD adoption in an emerging market is also hindered by ineffective profit distribution procedures, a low level of stakeholder trust, inadequate training, a lack of technological support, a lack of legal and contractual support, procurement problems, and a lack of a collaborative environment (Othman, 2020). An extensive literature review has revealed the following barriers categories: technological barriers (Durdyev et al., 2019), financial barriers (Georgiadou, 2019), lack of adequate research on IPD (Othman, 2020), cultural barriers (Sherif et al., 2022), and legal barriers (Rached et al., 2014). Despite the variety of barriers identified in the literature, this study focuses on the technological barriers and the potential of advanced technologies, i.e., blockchain and smart contracts, in addressing them.

POTENTIAL OF BLOCKCHAIN AND SMART CONTRACTS IN CONSTRUCTION

In recent times, blockchain technology has been introduced as a distributed ledger that can assist project teams with information decentralization and security (Assaf et al., 2022). Besides providing secure and reliable databases, it also promotes various payment transactions among project parties. Numerous benefits are perceived by the adoption of blockchain technology, such as trustworthiness, immutability, and traceability (Assaf & Zayed, 2022). Furthermore, blockchain technology has provided an efficient platform for the implementation of chaincodes (smart contracts) and automated transactions. Smart contracts can be defined as digital protocols that run on a selected blockchain network and enforce endorsement policies, as well as provide automated transactions (Ahmadisheykhsarmast & Sonmez, 2020). To this end, the association between blockchain technology and smart contracts has introduced a potential solution to address some of the IPD adoption barriers, such as the ineffective risk/savings distribution mechanisms (F. Elghaish et al., 2020).

Many studies have discussed the use of blockchain/smart contracts in the construction industry and, more particularly, in managing contracts and payments. Saygili et al. (2022) have discussed the application of blockchain in the reduction of construction disputes. Their study concluded that blockchain technology provides enforceable codes for transaction execution and efficient documentation of all of the transactions, minimizing the probability of disputes and claims. Moreover, Assaf and Zayed (2022) have studied the implementation of an integrated blockchain-based smart contracts system with BIM technology in automating the payment transaction in modular construction projects. Their study provided a claim resolution system to reduce the possible claims in modular projects. Elghaish et al. (2022) have developed a payment system to automate transactions in accordance with traditional and design-build delivery systems. Their study took into account the defects liability period (DLP) through the use of chaincodes to manage the remainder of the duties. Sonmez et al. (2022) have studied the integration between BIM models and decentralized blockchain networks to manage the project's progress payments. Furthermore, similar approaches of integrating BIM technology with supporting technologies were addressed to enhance construction procurement processes. For instance, Aguiar Costa and Grilo (2015) proposed an e-procurement system integrated with BIM technology to reduce the fragmentation in the procurement processes throughout the project life cycle. Different blockchain platforms were used in the mentioned studies, which raises the question of what indicators must be considered when selecting the blockchain platform. The following section will discuss the suitability of different blockchain platforms in the current study.

SELECTING THE SUITABLE BLOCKCHAIN PLATFORM

Several forms of blockchain platforms are available and vary in their functionality and level of privacy (Assaf & Zayed, 2022; Li et al., 2022). Some of the most used platforms are Ethereum, HyperLedger Fabric, Bitcoin Network, and R3 Corda (Perera et al., 2020). These platforms vary in many characteristics that specify their suitability to adopt for different purposes. Generally, blockchain platforms can be permissioned or permissionless. The permissioned blockchain platform allows certified participants only (with digital identity) to join the network. Conversely, the permissionless blockchain network, such as the bitcoin network, allows anonymous participants to join the network (Li et al., 2022). The characteristics that govern the selection of blockchain platforms include the following: permissioned or permissionless, support of smart contracts implementation, confidentiality, scalability, support of consensus mechanism, and batch size (Perera et al., 2020). Therefore, the developer of the network must consider all of these characteristics prior to the selection of the platform. In this study, the chosen blockchain platform is expected to satisfy the following criteria: 1) it should be permissioned to allow the creation of private channels; 2) it should support the creation of smart contracts; and 3) it should be able to handle a large number of transactions. Therefore, considering all of the mentioned selection indicators, the Hyperledger Fabric platform was selected in this study. More on the selection of the platform and architecture of the selected one will be discussed in the following section.

METHODOLOGY

In light of the previously mentioned aims and objectives, Design Science Research (DSR) is adopted as a methodology to achieve the purpose of the study. Generally, DSR is composed of three main parts, which are problem identification, solution design, and solution evaluation (Offermann et al., 2009). As already stated, there is a deficiency in the current payment system when implementing IPD. Therefore, the solution design consists of employing blockchain technology to overcome this issue, and the solution evaluation is done by validating the model by testing it on a real case study. As *Figure 1* illustrates, the model is divided into three main stages: the conceptualization stage, the implementation stage, and the validation stage. First, the conceptualization includes identifying the research's main objectives and the theoretical framework of the research methodology. Furthermore, the implementation stage includes the development of two interconnected systems: the BIM models and the smart contract-based blockchain system. The development of the BIM models includes 3D, 4D, and 5D BIM models. These models were used to feed data to the smart contract-based blockchain system. The development of the smart contract system includes many steps: assigning certificate authority for each participant, identifying the public and private channels, identifying the endorsement policy for the transactions, developing the smart contract (chaincode) in accordance with the endorsement policy and the contract requirement, and building an end-user application to ease the interaction with the blockchain network.

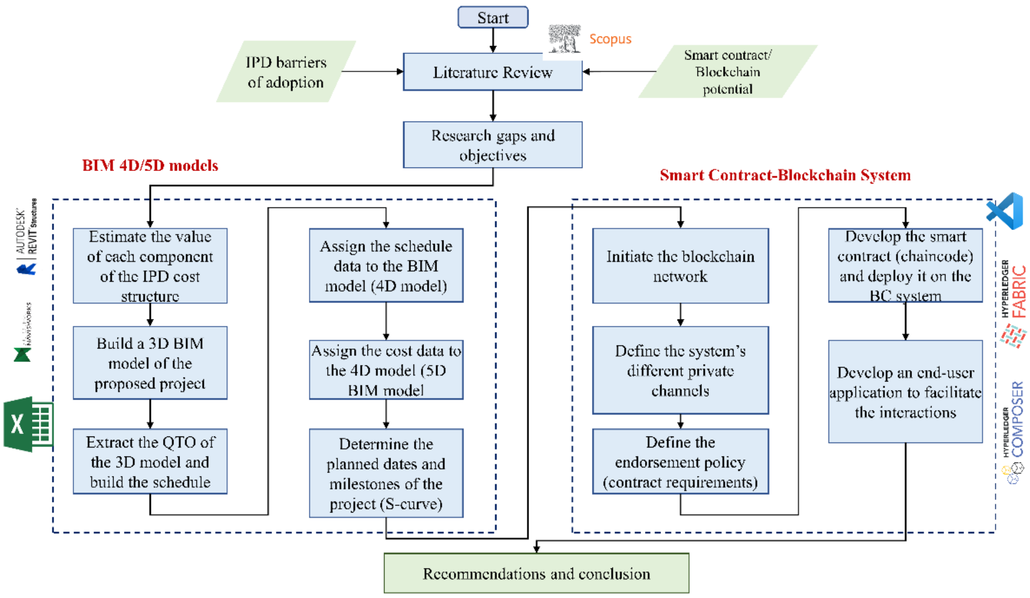

Figure 1: An overall framework of the solution design

One critical part of the developed systems is data flow. The data is considered interchangeable among the developed systems. Figure *2* shows the flow of data among different systems. The development of the 3D BIM model requires 2D drawing (if BIM was not adopted since the project's start). The quantity take-off (QTO) for all elements is exported to Excel sheets to perform the needed calculations. The 3D BIM model is then exported to Navisworks. The estimated durations and costs by Excel are also imported to Navisworks to build the 4D/5D BIM models. Milestone data and planned values are then deployed on the smart contract, as well as the endorsement policy. The endorsement policy can be defined as a protocol to check the validity of the submitted payment requests. Finally, the developed overall system is deployed on the Hyperledger Composer tool to provide an end-user application.

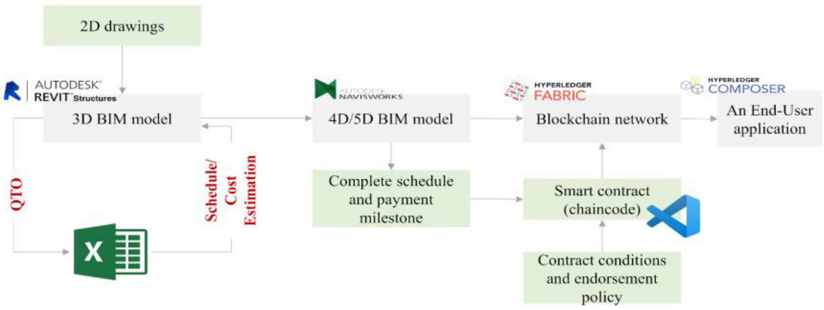

Figure 2: the flow of the data through different systems

4D/ 5D BIM Models

BIM models developed in this step contain geometric and parametric information, which is expected to assist owner and non-owner participants in estimating accurate costs and schedules (Amin Ranjbar et al., 2021). The accuracy of the estimation of the cost and schedule significantly depends on the level of model details. After the 3D BIM model development, the objects (elements), the quantity take-off (QTO) is exported to Excel sheets so that it can be processed by the project management team (PMT) office without the need for a high level of BIM experience by the employees (Amin Ranjbar et al., 2021). Needed materials, unit costs, labor resources, and equipment resources are retrieved by the participant procurement team. Navisworks tool is used to build the 4D BIM model by integrating the schedule data into the 3D BIM model developed by the Revit Structure tool. Moreover, the 5D BIM model is generated by integrating the cost data into the developed 4D BIM model on the Navisworks tool. The developed BIM model is considered to have a level of detail (LOD) of 300, as it covers the following criteria: precise information on quantities and cost and schedule data (Latiffi et al., 2015). It is worth mentioning that the payment figures for the IPD project follow the LIMBS cost structure that will be discussed in the below section.

IPD COST STRUCTURE

This section illustrates the IPD cost arrangements and characteristics. As mentioned before, the compensation (sharing) system forms a critical part of IPD projects (Elghaish et al., 2019). IPD participants usually go through multiple validation phases prior to the start of the project to agree on the sharing ratio (Thomsen & Faia, 2009). This sharing system must specify the distribution of the risk/profits when cost overrun or underrun occurs. As addressed by Elghaish et al. (2019), integrating BIM with the IPD system can facilitate the compensation system through the early involvement of participants. This can be done by developing 4D and 5D BIM models to have a reliable budget and cash flow for all participants before deciding profit/risk ratios. Ross (2003) states that the compensation system of IPD projects generally follows the '3-LIMB' (components) method. Figure 3 illustrates the characteristics of the 3-LIMB method.

Ross (2003) explained LIMB 1 as the direct costs paid by the contractor plus the overheads of this particular project. The reimbursement of LIMB 1 is guaranteed for the contractor and is not subject to the value of LIMB 3. LIMB 2 represents the agreed profits and general office overheads. Unlike LIMB 1, LIMB 2 is subject to the condition of the submitted payment request by the contractor. In other words, if the submitted value exceeds the target value, the reimbursed cost will be subtracted by the risk share ratio stated in the contract. The final reimbursed cost should not be less than LIMB 1. Each of the mentioned LIMBs is calculated based on a set of equations. The following sections will illustrate the equations included in calculating each LIMB.

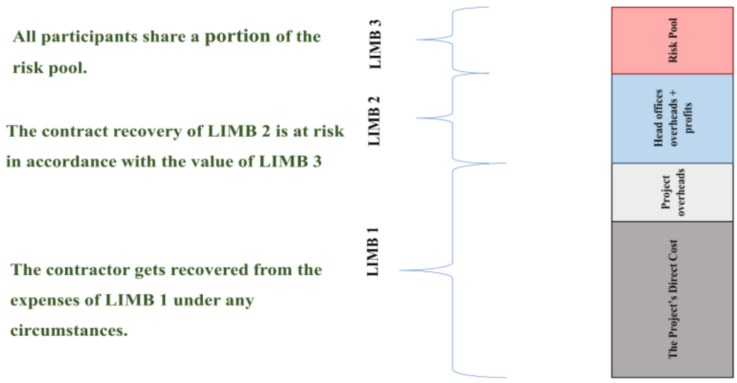

Figure 3: the cost structure of IPD projects

IPD COST ESTIMATION

This section demonstrates the formulation of each LIMB in the IPD system. The presented equations are retrieved from (Elghaish et al., 2019), (Faris Elghaish et al., 2020), and (Ross, 2003). Equation 1 shows the estimation of the LIMB 1 value. It is worth mentioning that the quantity of work used to estimate the direct cost is extracted from the 3D BIM model.

$$LIMB1_{ij} = \sum_{j=1}^{n} (CoDA_{Kj} + CoIA_{Kj})$$ Equation 1

Where $CoDA_{Kj}$ is the direct cost for contractor i to perform activity k in work package j. On the other hand, $CoIA_{Kj}$ is the indirect cost incurred by contractor i to perform activity k.

Furthermore, the estimation of value for $CoDA_{Kj}$ can be calculated using Equation 2, as mentioned by (Assaf & Zayed, 2022).

$$CoDA_{Kj} = \sum_{k=1}^{n} (MC_{kt} + LC_{kt} + EqC_{kt}) \quad \text{Equation 2}$$

Where MC_{kt} is the material cost for activity k at a particular time t, LC_{kt} is the labor cost for activity k in a particular time t, EqC_{kt} is the material cost for activity k at a particular time t. On the other hand, $CoIA_{Kj}$ is generally calculated as a ratio of $CoDA_{Kj}$, considering the fixed and variable indirect costs.

As mentioned above, LIMB2 accounts for the pre-defined profits and general office overheads. The office overheads can be calculated in accordance with the approach followed by Elghaish et al. (2019). The profit ratio is applied to the total cost calculated in LIMB1 and was added to the equation following the illustration of the IPD cost structure by Ross (2003). Equation 3 shows the method followed to calculate LIMB2.

$$LIMB2_{ij} = \sum_{k=1}^{n} (NOA_{OK} \times MVOCD_{k}) + \%PR \times LIMB1_{ij} \quad \text{Equation 3}$$

Where $LIMB2_{ij}$ represents the profits and office overhead cost for contractor i to perform work package j. NOA_{OK} is the number of operations O needed to perform activity k's overheads. Further, $MVOCD_{k}$ represents the cost of one operation needed to perform activity k. $\%PR$ represents the pre-agreed profit ratio in the contract.

LIMB 3 value represents the amount of money saved (or additionally incurred) compared to the target value specified in the contract. The value of LIMB 3 is added to the risk pool of the project and shared with all of the nonowner participants in accordance with the adopted compensation system. The value of LIMB 3 can be calculated as in Equation 4.

$$LIMB3_{ij} = MVP_{ij} - (LIMB1_{ij} + LIMB2_{ij}) \quad \text{Equation 4}$$

Where $LIMB3_{ij}$ is the monetary value added to the risk pool and incurred by contractor i to perform work package j. MVP_{ij} is the monetary value planned in the contract to perform work package j.

THE BLOCKCHAIN NETWORK

As mentioned above, many blockchain platforms are available and can be adopted across various industries (Perera et al., 2020). To achieve the study objectives, three main indicators were used to select the appropriate blockchain platform. These indicators can be summarized as follows: First, the chosen platform should support the involvement of smart contracts (chaincodes). The smart contract feature is an essential component of this study as it defines how the automated transactions are executed. Second, the chosen platform should be permissioned and allow the creation of private channels. Channels provide privacy between two participants when needed, such as sharing information between the owner and contractor. Third, each platform has a block size that determines the maximum number of transactions that can be included in one block. The Hyperledger Fabric platform was selected for the study to build the blockchain network. Many components are included in the Hyperledger Fabric platform, among which, seven main components are considered to reach the research objectives. These components are the peers, ledgers, smart contract(s), orderer(s), channels, end-user applications, and certificate authorities (CAs).

SMART CONTRACT AND PERMISSIONS

This subsection illustrates the formation of the smart contract. The smart contract specifies the endorsement policy by which the submitted transactions are evaluated. The transactions included in this study reflect the payments in the context of IPD projects and cost plus with target value contracts. However, the developed smart contract can be reconfigured to suit any delivery method and contract type. Many functions are included in the created smart contract and can be summarized as follows: 1) to validate the submitted transactions against the identified endorsement policy; 2) submit payment by the contractors to the owner; 3) pay the valid payment request by the owner to the contractor; 4) calculate the limbs and allocate the right transactions to all participants. Furthermore, the developed network is permissioned, meaning that not all participants have the ability to view each component of the network. These permissions are used to enforce access control for participants. For instance, contractor *i* does not have access to submit transactions to other contractors in the network. Figure 6 shows a sample of the permissions given to participants in the Hyperledger Fabric network.

IMPLEMENTATION AND RESULTS

This section presents a case study of a residential building constructed in Cairo, Egypt. The building has ten floors and a floor area of 600 m2. The presented case study is used to validate the proposed methodology. The project was done using cost-plus (with target value). Autodesk Revit was used to develop the 3D BIM model. Figure *4* shows the developed BIM model. The QTO of the project is exported to Excel Sheets, and the total cost and duration were calculated.

Figure 4: the 3D BIM model

4D/5D BIM MODELS

The developed schedule was added to the 3D BIM model to develop the 4D BIM model. Autodesk Navisworks tool was used to develop the 4D BIM model. Figure 8 shows the developed 4D model. Bar charts are presented for each activity to demonstrate the calculated durations. Furthermore, the cost data was integrated with the 3D BIM model to develop the 5D BIM model. Figure *5* shows the 5D BIM model. The 4D and 5D BIM models are used to estimate the target values for the project (schedule and cost).

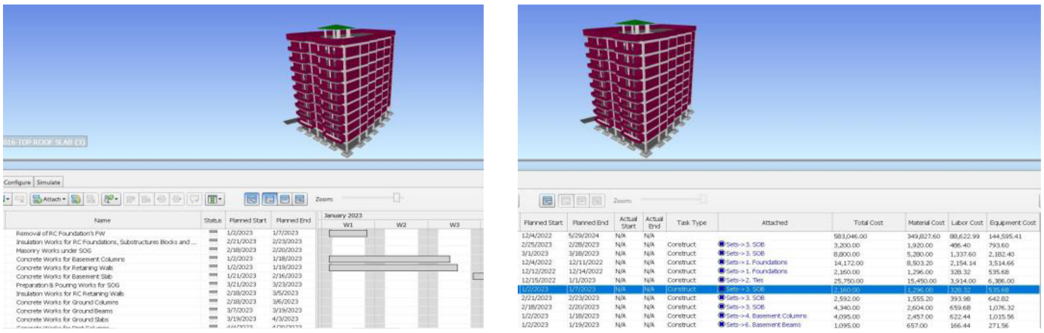

Figure 5: the developed 4D/5D BIM models by Navisworks tool

DEVELOPING THE SMART CONTRACT

In the proposed system, the contractor submits a payment request following the agreed milestones of the project. Therefore, the project PMT develops an S-curve specifying the planned dates and costs (targets). The contractor is expected to submit this payment request on the blockchain system, and the submitted request will be evaluated based on the endorsement policy. The contractor's reimbursement of the incurred cost depends on the target cost for the corresponding milestone. The cost overrun will be shared with each participant in accordance with the agreed sharing ratio. Similarly, the savings will be shared with all participants according to the sharing ratio. The developed smart contract has many functions. Figure 6 shows the transaction part of the smart contract. The smart contract code was written using two main languages: JavaScript and Hyperledger Composer. The code automatically calculates the three values of limbs. It also uncovers whether there are cost savings or cost overruns in accordance with the target values. Moreover, the code acts when the target cost is exceeded and modifies the reimbursable cost according to the cost structure of the IPD approach. Other functions of the code are claims submissions and extending the completion date by the owner. The following section will illustrate the outputs of the developed system.

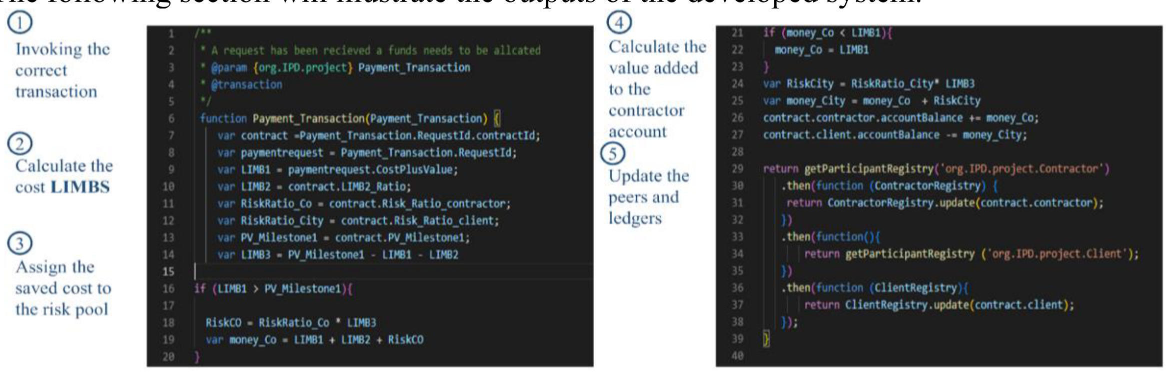

Figure 6: the transaction code on the smart contract

END-USER DEVELOPED APPLICATION

All of the code is integrated into the Hyperledger Composer tool to facilitate interactions among all participants. Figure *8* shows the interface of the end-user application. The system allows only specific participants to add private channels, which must be verified by the network orderer. The accessing participant is only eligible to read, create, update, and delete assets that are within their scope. This access control is implemented using the ACL feature of Hyperledger Composer. Transactions are governed by hash values, meaning that any amendment of a previously invoked transaction can be easily located on the network, enhancing the trustworthiness among participants.

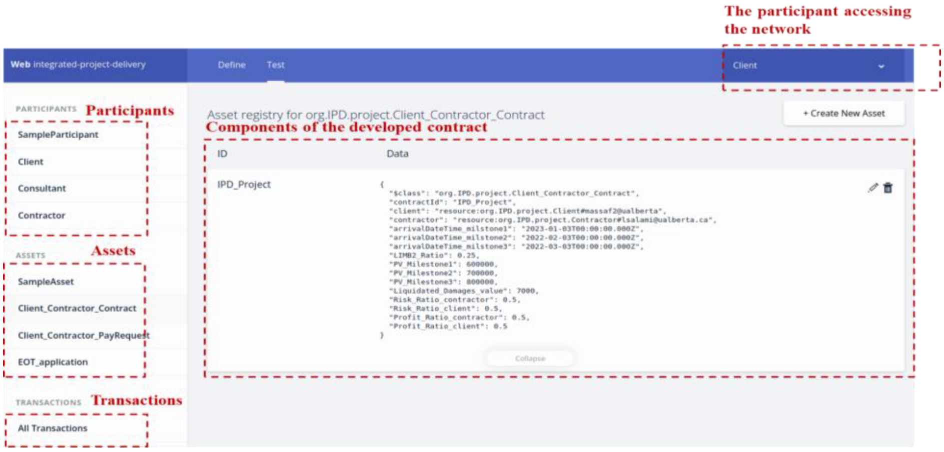

Figure 7: the interface of the developed end-user application

Figure 8 shows a closer look at the formed contract on the network. The contract specifies all the attributes of the IPD projects and is accessible to all the individuals that are part of it. It specifies the included participants, target values, target costs, and sharing ratios. Furthermore, this efficient documentation of the transactions and movements can help minimize possible conflicts and disputes. Despite the contribution of IPD in minimizing possible conflicts, claims still exist according to the clauses mentioned by CCDC-30 (2018) that need to be minimized.

Figure 8: the developed smart contract presented on the blockchain network

CONCLUSIONS

This study is motivated by the lack of research on practical solutions to the technological barriers of IPD adoption in construction projects. It presents an integration of the IPD delivery system with innovative technologies to overcome deficiencies in payment systems, which forms a barrier to IPD adoption. The proposed approach develops 5D BIM models that feed various data, such as milestone dates, into the developed blockchain network that uses the Hyperledger Fabric platform. A smart contract representing the cost structure of the IPD project is developed and employed on the developed blockchain network. The developed smart contract enforces an endorsement policy that verifies the validity of the submitted transactions by the project parties. Additionally, the developed blockchain network provides access control, allowing the corresponding participants only to submit (or issue) transactions. The model provides fair profit and risk-sharing among project participants.

This study contributes to the body of knowledge by: 1) providing a secure automated system that can promote the IPD adoption in construction projects; 2) providing efficient documentation that can help minimize possible claims; 3) developing a system that can be reconfigured to suit other contract types and delivery methods; 4) providing an automated sharing of risks and gains through smart contracts, without the need to involve third parties. Despite the contributions provided by the presented study, it still includes some limitations. The development of the smart contract is considered complex and could include human errors. Furthermore, the developed system supports only extension of time claims. Future research may also consider more types of claims submission, such as loss of productivity claims. Future studies can also focus on integrating financing strategies, such as joint ventures, in the developed system.

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LEAN SUPPORTING A FRAMEWORK FOR THE CONSTRUCTION INNOVATION PROCESS

Bernardo Martim Beck da Silva Etges[1] and Carla Schwengber tem Caten[2]

ABSTRACT

The construction sector has gradually been restructuring to advance the use of digitalization and taking advantage of Industry 4.0. Recent studies in the IGLC Community have emphasized the need to connect Lean Construction with the innovative movement by promoting and advancing the use of Industry 4.0 technologies. However, it is well known that innovation approaches are successful when they achieve the goal of problem solving. Considering this context two questions are set: (a) Does the innovation process in construction sector understand how to capture pain-points of the industry and in how it organizes itself? (b) Does Lean Construction contribute by offering a conceptual basis for reaching a better understanding of innovation? This paper aims to develop a framework for analyzing and catching the pain-points as the starting point for the innovation process. As a result, a Problem-space-framework (PSF) was proposed and validated in a empirical study. The first question was tackled by conducting a qualitative analysis and holding a workshop, the outcome of which was that eight out of 98 pain-points identified were prioritized towards the solution design. The second question was also fully answered identifying that 89% of the participants understood that Lean Construction contributed to the PSF and most of Lean tools proposed were regarded as having high usability during the implementation phases.

KEYWORDS

Lean construction, innovation, pain-points, problem-space-framework

INTRODUCTION

Throughout history, humans have managed to innovate and evolve different industrial solutions, to improve their labor processes but also, and, to a greater extent, their wellbeing (Noueihed, K., Hamzeh, F., 2022). Considering that innovation is needed in industry to enable a better quality of life, we may also say that innovation in a business environment defines the organization's ability to create and achieve competitive advantages that can generate a range of sustainable opportunities (Aranha, 2016). According to Audy and Piqué (2016), society now has a strong base that is founded on the knowledge of highly qualified professionals and teams, in addition to which this is reinforced by new technologies having been developed and mastered. These factors give society a new characteristic which focuses on knowledge and innovation.

An analysis of the construction industry shows that it configures an important pillar of the economy in many countries since it contributes greatly to GDP and is a major employer. However, construction is perceived as a sector that lags behind other industries with regard to innovation (Wang et al., 2021). A plethora of studies regarding many countries acknowledges

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that construction falls behind other industrial sectors in relation to improving productivity (Vrijhoef and Koskela, 2000, Kapelko et al., 2015, Zhan et al., 2018). Productivity in the construction industry is still described as having scarcely evolved, being nearly stagnant in the last 20 years and there having been a low rate of investments in digitalization and innovation (Mckinsey, 2017). However, the characteristics of the ecosystem of construction can pose several obstacles to innovation. These include the temporary nature of the relationships in construction projects, which hampers the exchange of knowledge and building trust between different parties (Greco et al. 2021) or due to construction having special operational characteristics, namely it is project-based, resource-intense and risk-related (Wang et al. 2021).

Given the above context, the next section of the article will undertake a panoramic review of the literature, considering the characteristics and main positions of the innovation process in the construction industry and its interfaces with Lean Construction. A gap in the literature and in knowledge is identified with regard to there not having been, hitherto, a structured process for identifying pain-points in the construction sector for innovation processes integrated with Lean Construction concepts and tools.

Therefore, this paper identifies an opportunity for developing practical proposals for guiding and implementing the innovation process in the civil construction value chain. The general objective of this paper is to develop a framework to analyze and capture pain-points as the starting point for initiating an innovation process in construction companies. To do so, two questions are set: (a) Does the innovation process in the construction sector understand how to capture pain-points of the industry in principle, and also, in practice, within a given company? (b) Does Lean Construction contribute by offering a conceptual basis for understanding innovation?

LITERATURE REVIEW

Lindgren and Emmitt (2017) state that technological innovation in construction depends on and involves a broad and complex network of stakeholders, from customers to product manufacturers and designers, contractors and end users. In addition, there is the relationship with governments and direct action with society to be considered. Seeking to identify these multiple relationships between stakeholders, Xue et al. (2017) and Larsen (2015) view the relationships of the innovation process as collaborative relationship networks and highlight the key roles that some parties play in the innovation process. The decomposition of collaborative relationships together with network analysis allowed a better understanding of the innovation process in construction. In particular, this enabled the so-called “real problems” that support the definitions of greatest impact regarding innovation to be identified (Xue et al., 2017). Taylor et al. (2006) had already concluded that, only by having organized and interdependent processes would significant performance improvements in innovation be achieved in the construction industry.

On the other hand, the focus of innovation research has tended to concentrate largely on traditional and hierarchical industries. When project-based industries are included in innovation studies, analyses rarely explore the implications for the organizational structure nor the specific characteristics of these industries with regard to the spread of innovation. Hopkins et al. (2011) suggested that project-based organizations are inherently more open than other organizations, and their efficiency comes from economies of the system, rather than from economies of scale. Hence, the paucity of studies on project-based industries and the Innovation Process is surprising.

Multiple authors have studied innovation in construction in terms of the product, new materials, building systems and design tools (Azhar, 2011). Their studies show that most companies generate innovative products and processes; however, they have difficulty in carrying out continuous and structured innovations (Pellicer et al., 2017). Viewing innovation as an organizational process, some studies in recent years have focused on the interrelationship between the various players and stakeholders. Network-based, inter-organizational arrangements emerged as new means to facilitate the development and spread of innovation within the construction industry (Keast; Hampson, 2007). According to Pellicer et al. (2017), innovation in companies in the construction sector needs to stop being a spontaneous act that only arises when the solution of a specific problem is found, and to become a systematized management process integrated with the development of knowledge. Larsen (2015) indicates the importance of building an integrated and flexible innovation network into a continuous process of developing solutions and knowledge where good practices can be used collaboratively (Pellicer et al., 2017, Larsen, 2015).

Recently, Hamzeh, et al. (2021) suggested an important topic considering innovation and technology. Even with the arrival of the "fourth industrial revolution" or Industry 4.0, the attempts of research to acknowledge the influence of Industry 4.0 on the architecture-engineering-construction (AEC) industry, have been primarily on technology. Some studies point out that Lean Construction has become a major tool for learning, collaboration and for sparking an environment of innovation. A survey developed by Trentim and Etges (2021) identified that 92.6% of their respondents understood that implementing Lean Construction supported the development of knowledge and critical analysis of problems and solutions. Christensen and Christensen (2010) Zhang and Chen (2016), Tyagi et al. (2015) and Skinnarland and Yndesdal (2012) have similarly demonstrated that projects that implement Lean Construction (LC) have huge potential for generating knowledge and are fertile areas for collaborating due to LC's characteristic of creating interdisciplinary and collaborative innovation. Taggart et al. (2014) argued that, when a collaborative and proactive environment is provided to supply chain partners, the root causes of defects are more likely to be identified leading to cost-effective solutions being proposed (Greco et al. 2021). Hamzeh et al. (2021) highlighted the need to connect LC with this new innovative movement by introducing Lean Construction 4.0 principles into established practices so as to keep pace with the advancing technologies of Industry 4.0.

In the current paper, we will seek to understand how "real problems" can connect with innovation in different construction phases, given a LC background, collaboration and technology (Hamzeh et al., 2021, Xue et al, 2017, Azhar, 2011, Taggart et al., 2014).

RESEARCH METHOD

The current paper is part of a broader research activity for a doctoral thesis by the first author. The stage described in this article covers the validation of the first construct within a broader methodological approach of Design Science Research (DSR). This paper was undertaken in 3 stages divided into two phases, as illustrated in Figure 1. The first phase took a broad view of the construction market in relation to innovation on the way to support the questions set. The second phase (which includes stages A and B) is a an empirical study developed in a construction company within the Brazilian real estate market.

The first phase consisted of determining how specialists in the sector understand the innovation process in the Brazilian construction sector. Hence, a qualitative study was engaged on which drew on the experiences and opinions of a group of professionals. The technique adopted was an open individual interview, using a semi-structured script. As to the method used, it took a qualitative approach. A group of professionals was invited to take part, in order to have additional opinions and content about the object of study. The distribution of interviews was planned in order to obtain a balance between the number of respondents in each segment of innovation, thereby seeking to ensure a diversity of responses, which is desirable in qualitative studies (VOSS et al., 2002).

Since this paper focuses on validating the first construct of a DSR, it is important to note that one limitation of the second phase is that it was conducted with a company that already has experience with Lean Construction methodologies. Based on the results obtained in Phase 1, Phase 2 aims to develop a model for implementing the innovation process in a civil construction company. Stage A of phase 2 seeks to develop a model for structuring the performance of the innovation process in order to allow for greater efficiency and to capture value due innovation. This step was based on the conceptual model of the Double Diamond (Design Council, 2016). The case study company has a corporate innovation strategy and has already been involved in a broad Lean Construction implementation project. Last year, it defined its objective as being to centralize its investments in improvements by strengthening the innovation process.

The Double Diamond model was proposed by the British Design Organization in 2005. The model emphasizes the analysis of a problem as the basis for building 4-phase solutions using two adjacent diamonds. The two diamonds are (i) the problem and (ii) solution spaces. In each space, a diverging phase that expands the space is followed by a converging phase that narrows the space (Zhang et al. 2019)

Finally, Stage B of Phase 2 seeks to understand if Lean Construction favors innovation. Thus, the third stage of the research aims to answer the second question by applying a questionnaire to those involved in Stage A, in order to capture perceptions and map possible benefits of or weaknesses in integrating Lean Construction into the innovation process.

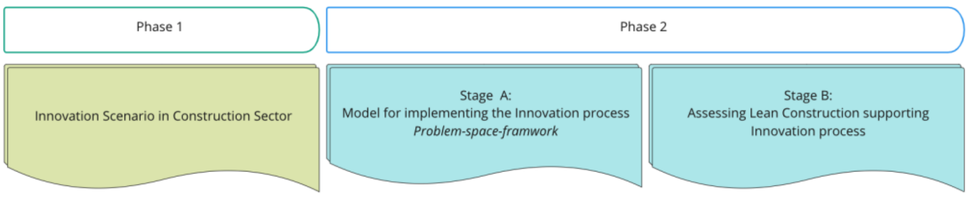

Figure 1: Structure of the Paper

RESULTS

Identification of the Scenario of Innovation in Civil Construction

The group of professionals chosen by the researcher was formed in order to elicit and add opinions and content about the object of study. Numerical representativeness is not the main focus, but it was considered important to have a diversity of respondents. By consisting of accelerator managers, innovation specialists and startup directors, the sample population is more likely to succeed in identifying gaps, generating insights and forming hypotheses. Thus, by adopting a qualitative approach, it is possible to explore the object of research in depth, because one can understand the cause-and-effect relationships and can seek ideas and new hypotheses (RIBEIRO and MILAN, 2004).

The interviewees were selected by the researcher who sought companies and professionals involved in the civil construction and engineering sectors, in innovation processes and who had taken part in founding startups in the sector. Eight interviewees were selected: (i) Two specialists in implementing innovation projects in engineering-based industries; (ii) Two managers of acceleration and open innovation programs, focused on the civil construction sector - the programs were selected considering that both had already concluded at least one complete cycle of acceleration; and (iii) Four Chief Executive Officers and founders of startups which have undergone at least one acceleration cycle and are already in the market operation phase. Choosing a startup was based on three criteria (a) it must be from the civil construction sector, (b) it already has a product, a Minimum Viable Product that has been validated, tested and is in the market phase, (c) it has undergone at least one full acceleration cycle.

The interviews were conducted, resulting in 6 hours of recordings. These recordings were transcribed into a text editor and compared to the notes of main topic notes made by the researcher during the interviews. After being transcribed, the interviews were prepared for analysis. Each of them was grouped according to the sequence of questions asked by the researcher using content analysis using the NVivo sotware

When questioning the interviewees about the perception of the innovation movement in Brazil, they all answered that it is a growing movement, but only one of the interviewees was openly optimistic: “I perceive that the movement has been gaining a lot of strength, but it seems to me that the people inserted (in startups, in companies and investors) are lost and so are the needs of the sector”. Five of the interviewees stated that it is up to companies and startups to better understand the pain-points of the sector to bring solutions that can add greater value to organizations: “The launch of a company as a result of a problem experienced, in my experience, is 50% of the success. Finding the problem is key to thinking about a solution.”

At the same time, six of the eight interviewees expressed apprehension regarding a certain trivialization of innovation and the loss of credibility of the proposed initiatives and solutions: “We are at a time when everyone has access to low-quality information, and therefore, there is much focus on "we need to innovate", "we need technology" without thinking about the real problem [...] There are solutions that generate zero value for the market. Not generating value compromises the fundamental objective of innovation processes. I fear the topic will become another "buzz-word" in the market. We must protect the innovation topic!”. Figure 2 shows the result collected from the content analysis of the interviews. All interviewees identify investments in innovation and the structuring of innovation processes in the construction sector are a growing movement, but they also associate the current situation with a certain pessimism. A large part of this sensation is due to the perception of the sector's difficulty in directing innovation actions and investments at the real problems and pain-points (six out of eight interviewees), which for also leads to the loss of credibility of innovation in the sector.

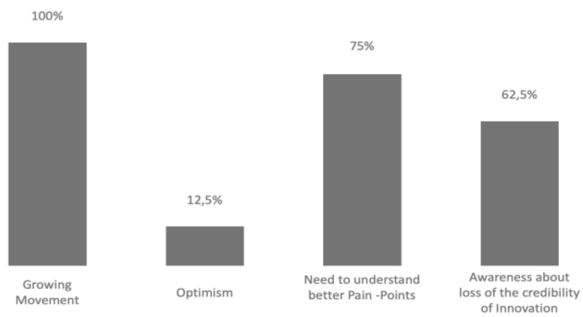

Figure 2: Perception of innovation in Brazil

Content analysis identified three main directions: (i) the movement towards innovation and access to new technologies is growing in the construction sector. However, (ii) there is a divergence between the interviewees about their perception of the value delivered by innovation initiatives and (iii) there is difficulty in measuring the results and impacts provided by implementing innovation in the construction sector.

Considering the above, two aspects can be raised that have an impact on the credibility and results of the solutions implemented in the proposed innovation processes analyzed. First, the gap in identifying the real pain-points or problems of the sector can make it difficult to understand what the innovation is (XUE et al., 2017, TAYLOR et al., 2006); second, the lack of definition of follow-up metrics and of a clear zero line distort, or make it impossible to understand, the result obtained.

MODEL TO IMPLEMENT THE INNOVATION PROCESS IN CONSTRUCTION SECTOR

The conceptual reference for the structure of the Workshop was that of the Double Diamond Framework. In the stage covered by this study, we are working on the first cycle of the diagram named Problem Space, seeking to Discover the problems and Define the actions. Figure 3 shows the association of the steps described with the Double Diamond Model.

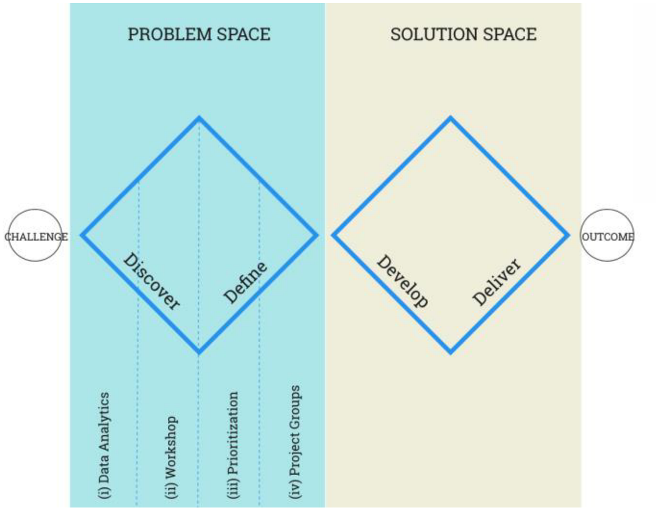

Figure 3: Double Diamond Framework adapted to the current research - Problem-space-framework (PSF)

Having obtained results from qualitative research conducted with specialists in the sector's innovation process, and having added these to the perception of a large-scale developer company in the Brazilian housing market, phase 2 of this study then set out to develop a model for guiding the innovation process of the company. To define this model, the current stage was divided into 4 sub-stages: (i) Preparation, carried out by collecting data and interviewing company representatives; (ii) Development and implementation of a model of a workshop on validating Pain-points; (iii) Prioritization of classification; and (iv) structuring of project teams to direct solutions to the Pain-points identified. For the first sub-stage, we made a comprehensive analysis of the company's budget, costs, and the performance of its supply chain. This involved a thorough examination of factors such as costs, savings, and construction terms. We also conducted open interviews with a group of site engineers and managers to gain a better understanding of the company’s current situation.”.

It should be noted that the company in the empirical study, which in this article is called Company A, has been investing for two years in a wide-ranging Lean Construction implementation project, a project that has already reached more than 150 construction sites. This consideration is important, as most of the leaders involved in this stage already participate in the Lean Construction project and are familiar with process design tools, how to identify causes and problem solving.

Company A has always held a prominent place in terms of innovation in the Brazilian Civil Construction market, featuring in important national awards (those given by the Brazilian sectorial journals); however, the team from the Innovation in Production sector has become aware of the difficulty of understanding, mapping and consolidating results of the multiple initiatives that were conducted. In addition, planning for the year 2023 required assertive investment planning in initiatives that addressed the company's real problems and pain-points. In numbers, the present situation covers 89 projects at some stage of implementation and with different levels of expected result and necessary investment, but without a clear governance to accompany them. Of this total of projects, 49 started from initiatives promoted by the Lean Construction project in the construction works. Nevertheless, their results have not been managed nor have the results and lessons learned from acting on these initiatives been disseminated throughout the company.

Considering the context described, we first sought to understand the main problems of Company A based on data analysis (Data Analytics) and interactions with the company's Production team. It is important to mention that the company has a large source of consolidated information in Data Analytics and Business Intelligence in Microsoft Power BI and a specific sector that guides the business strategy and compiles and publishes indicators of the productive processes. At the same time, a questionnaire was sent via Google Forms to those involved in the production process. 42 responses were obtained, 6 from directors, 11 from managers, 5 from engineers, 3 from Backoffice consultants and 17 from Lean Construction project consultants. As a way to ensure more managers listen to what kinds of problem occur during production, two online workshops were held attended by 15 engineers from the company. They listened to and discussed openly the main problems that impact their production activities. As output from these three sources of evidence, five pain-points were addressed: i) Quality of budgeting; (ii) Site productivity; (iii) Management of metal forms; (iv) Excessive bureaucracy for services and materials supply chain; (v) Terms in design and construction phases. Regarding the strategic position of the data for Company A, the pain-points could not be detailed in the current paper for reasons of confidentiality

This base of pain-points identified was presented and made available as a reference for the leaders group that was elected to participate in the 1st Workshop on Innovation in Production. 30 leaders (directors, managers and engineers) and 6 moderators participated in an immersive and face-to-face workshop held to reach a more detailed understanding of the production Pain-points of Company A in order to structure innovation project plans for 2023. The one-day Workshop was structured as per the sequence below. The outputs are shown in Table 1:

- (i) Pain-points brainstorming: based on the previous analysis of the data, the participants were divided into 5 working groups and by using mind maps or brainstorming dynamics they discovered the pain-points that they identified that impact production. In this stage, the groups mapped 98 pain-points;
- (ii) Prioritization of pain-points: in the second stage, the groups were asked to prioritize pain-points using an effort versus impact matrix. 26 pain-points were listed;
- (iii) Design-sprint for prioritizing pain-points: Each group took the pain-points prioritized in a table that was divided into 10 themes corresponding to Company A's enterprise cycle. which for them were the ones that had the most impact on production. 8 pain-points were prioritized;
- (iv) Linking projects in progress to the pain-points mapped: In the end, the 89 projects at some level of development and already distributed in the 10 themes of the company were made available to the groups The working groups then linked these projects to prioritized pain-points. Of the 89 initial solutions, it was found that 35 would address prioritized pain-points.

The third phase of structuring the innovation process consisted of analyzing prioritized outputs and understanding whether the projects really address the pain-points and which projects will be selected for the 2023 strategy. To do so, a senior management group was formed consisting of the Vice-President of the company, 5 directors and the Innovation team. The post-workshop stages first of all positioned the pain-points and solutions in the progress of the development project, from business planning and real estate development, through the pre-work stages and execution of the construction work, to the delivery and post-delivery technical assistance. A critical analysis of the 35 listed solutions was made to determine the degree to which they actually solve pain-points. Of these, 28 solutions can address 7 listed pain-points satisfactorily.

Table 1: PSF Workshop outputs

Phase	Mapped Pain-points	Linked Solutions
Pre-Workshop	5 Main Pain-points discovered	89 Projects
Brainstorming to identify Pain-points	98 Mapped Pain-points	
Matrix Prioritization	26 Prioritized Pain-points	
Design Sprint	8 Selected Pain-points	35 Potential Projects
Senior management group Analysis	7 Prioritized Pain-points	28 Potential Projects 4 working groups

Finally, senior managers deliberated on the progress of the undertaking, the pain-points identified and the related solutions. Of the eight pain-points identified in the Workshop, seven were prioritized by the senior managers. (1) and (2) are related with commercial strategy, (3) and (4) are related with budget information and accuracy; (5) is related with labor turnover; (6) concerns the planning and construction terms and (7) the effort and bureaucracy needed to control costs and monitor productivity. These seven pain-points were classified into 4 categories and addressed to 4 specific working groups.

It is important to note that there is a convergence of seven prioritized pain-points with those identified in the first stage of Discovery by consulting the analysis and data collection from Company A. Three of the five pain-points identified during the Pre-Workshop phase were maintained and attested to during the Problem Space (Data Analytics, Workshop, Prioritizing and Project Groups): Quality of budgeting, Site productivity and Terms in design and construction phases are still in the final seven main pain-points. The second stage of the Diamond, the Solution Space, is the subject of the next steps of this research.

INTERFACE OF THE INNOVATION STRATEGY WITH LEAN CONSTRUCTION

To meet the second specific objective, this section summarizes the analysis of a survey regarding the perception of possible contributions of Lean Construction in the innovation process. As a first output, 49 of 89 projects were identified with Lean Construction and possible solutions in progress came from approaches of operational improvements catalyzed by the Lean Construction Project, which shows the relevance of the philosophy applied. In the second moment, the participants were invited to fill out an online survey form in order to evaluate in the first stage the level of involvement in the Lean Construction project and then to evaluate to what extent Lean contributes to the participation, knowledge of tools and approaches proposed in the Innovation Workshops

The Form was sent to all participants of the Innovation in Production Workshop or any of its working groups. We had received 26 responses and among the respondents, 18 (69%) had also taken part in the Lean Construction implementation project. For these 18, the Form led them to a specific section with the aim of evaluating the Lean Construction project and its relationship with the Innovation Workshop. In the first question, 14 participants said that they had a high (44%) or very high (33%) level of involvement in the Lean Construction implementation project and assessed their knowledge of Lean as high (39%) or very high (33%).

In the question "In your opinion, how much did Lean Construction contribute to the development of Innovation in Production projects?" 16 participants (89%) answered that Lean's contribution to the Innovation Workshops was high (39%) or very high (50%).

In the third section of the Form, where all the participants responded, the aim was to evaluate their perceptions regarding the format, model, and methodology used in the Innovation in Workshop. The first question was to evaluate the Workshop. The answers were categorized as:

- Methodology, where 69% responded "Very Good" and 31% "Good";
- Tools presented, where 81% responded "Very Good" and 19% "Good";
- Moderation, where 69% responded "Very Good" and 31% "Good";
- None of the dimensions were evaluated by the participants as "Bad" nor did any participant respond that he/she was "Indifferent" towards a dimension.

The answers to the question "How do you evaluate your ability to use the tools proposed in the Innovation in Production Workshop?" are presented in Figure 4. Note that the 5 Whys and Problem-Solution Fit Canvas tools are the ones that were best evaluated i.e., the participant stated that his/her skill in using these tools was high. And the Cause and Effect Diagram and the 5 Whys are the ones which 95% of the participants demonstrated that their skill in using them was average or high. It can be seen that these are tools that interact very well with Lean and indirectly this may have influenced participants to consider they had mastered using them.

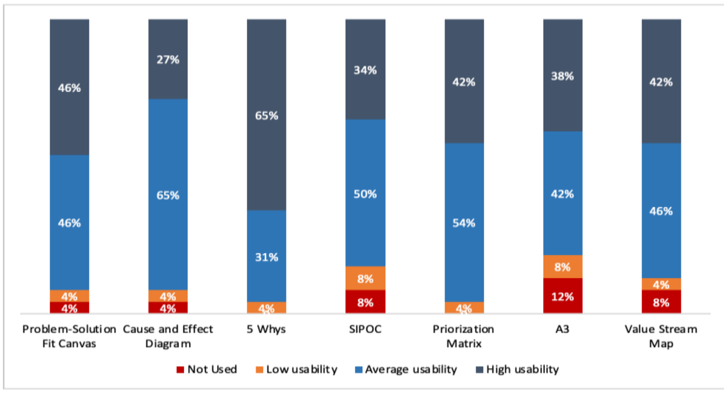

Figure 4: Usage of tools proposed in the Innovation Workshop

DISCUSSION AND CONCLUSIONS

Considering the main objective of this paper is to develop a framework to analyze and identify the pain-points as the starting point for the innovation process in construction companies, this objective was met. This was achieved by developing a model based on the Double Diamond that allowed Company A, in the case study, to direct its approach to a solution by basing it on a deeper understanding of the problem and of the pain-points of its processes and of the market in which it operates. The PSF presented seeks to deepen the understanding of pains by undertaking the steps of (i) conducting data analytics and promoting a collaborative understanding of identifying and mapping pains and by (ii) mounting a collaborative workshop. In the second dimension of the first diamond, we sought to define the focus problem through approaches of (iii) prioritization and (iv) definition of project groups and a work Roadmap. As already mentioned in the literature review, it is only by conducting organized and interdependent processes that significant improvements in performance due to innovation can be achieved in the construction industry and thereby enable the so-called "real problems" to be identified that support the definitions of greatest impact regarding innovation (Taylor et al.,2006; Xue et al., 2017). By providing a comprehensive understanding of pain-points and aligning them with a series of multi-collaborative workshop phases, the Framework focused on the Problem-space offers an innovative approach to the innovation process in the construction industry. This approach not only allows teams to address the real cause of problems more effectively, but also fosters a culture of collaboration and innovation that can drive long-term success. Figure 3 illustrates the PSF developed and validated in the case study. As results of applying the PSF, we have prioritized 98 pain-points and thereby reduced the number of main pain-points to 8 which will be directed as leverage for designing a solution.

The first research question was validated using qualitative analysis with interviews of experts, which showed that the construction industry is at risk of losing the benefits of its innovation processes and investments due to a lack of directing itself towards the pain points and problems of the sector. A lack of understanding of these pain points makes it difficult to measure and perceive the value of improvements made due to innovative initiatives. The use of discourse analysis revealed that this observation was the view of six out of the eight experts consulted.

Regarding the second research question, it was validated by the participants' perceptions during the Workshops and the proposed PSF that Lean Construction plays a significant role as a conceptual foundation and collaboration environment for fostering innovation. The results showed that 89% of the participants understood acknowledged that the Lean Construction project contributed to the Innovation Workshop, and 46% of them recognized that participating in Lean Construction routines was an effective way to prepare their teams for the Innovation Workshop. Furthermore, the participants evaluated all the tools used in Lean Construction routines as having a high or medium level of usability, with the 5 Whys and the Problem-Solution Fit Canvas standing out with 65% and 46% respectively of participants regarding them as having high usability.

It is worth emphasizing that the themes prioritized during the workshop phases are interconnected and cover the entire life cycle of construction projects, from commercial strategy to construction control. This holistic approach considers key aspects such as project design, budgeting, planning, and productivity in the field, and it recognizes the cause-and-effect relationship between decisions made in the early stages and their impact on construction sites. By taking this comprehensive view, teams are able to identify pain-points and develop effective solutions that drive long-term success.

Finally, while this study is part of a broader research effort and represents the initial exploration of a DSR approach, we can affirm the effectiveness of the proposed PSF framework. Although there may be improvement opportunities, such as to improve aspects regarding the prioritization tools and methods used, or the timing and duration of workshops, the results validate the model's efficiency both in prioritizing pain-points and in the perception of benefits by the teams involved. In line with our research plan and with the goal of continuously improving the model, we will conduct a further round of review and application of the PSF at Company A, to further validate the framework and explore its potential for implementation in other construction companies.

It is important to note the limitations of this paper, which is based on a single implementation cycle in one specific real estate company, that had undergone a Lean Construction project. This limitation is an improvement opportunity for future research as to implementing the PSF in different companies and also in those that are not working with Lean. Another important limitation is that, given the phase of the ongoing projects in the 4 working groups, it has not yet been possible to measure the effective results of the project. It is estimated that the first results will be measured at the end of the first 12 months after the workshop. Therefore, it is estimated they will become available in October 2024.

The use of PSF for defining the strategy for the Innovation process emphasized the significance of an unencumbered approach to innovation. The outcomes of the PSF emphasized that limiting the development of improvements can hinder progress in the innovation process. The 4 stages of the PSF strengthened the link between continuous improvement methods, such as those practiced in Lean Construction, and their relevance in the wider context of innovation.

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ZOOMING INTO WORKERS’ PSYCHOLOGY AND PHYSIOLOGY THROUGH A LEAN CONSTRUCTION LENS

Lynn Shehab[1] and Farook Hamzeh [2]

ABSTRACT

Lean construction has long been a constant advocate for perceiving humans as the driving force for most ventures and projects. Among the enablers of investigating the potentials and capabilities of humans are wearable sensors for collecting physiological measurements. Current research on wearable sensors in construction has not yet touched on its applicability or integration with Lean construction. Therefore, this conceptual paper “zooms into the workers’ psychology and physiology through a Lean construction lens” by exploring the potentials of employing wearable sensors in Lean construction. It aims to revamp current applications of wearable sensors by providing a comprehensive overview of the current state of wearable sensor technology and its applications in the construction industry. It also discusses how current studies on wearable sensors may be linked to Lean construction principles and how Lean concepts can further enhance and foster their potentials. The paper concludes by presenting the future possibilities and directions of wearable sensors in Lean construction and the impacts they can have on the industry.

KEYWORDS

Wearable sensors, physiology, psychology, measurements, Lean construction.

INTRODUCTION

The seemingly inexorable march of new technologies has rendered some industries negligent of not only the wellbeing of humans, but also their unexploited potentials that got concealed under the new technologies’ alluring capabilities. Industry 5.0, a successor to Industry 4.0, has emerged as a supporter for human-centricity, sustainability, and resiliency, which have somehow been overlooked in Industry 4.0 (Leng et al. 2022). A long-standing advocate for human-centricity is Lean management generally, and Lean construction specifically, which bears “people” as a main pillar to its core people-processes-technology triad (Hamzeh et al. 2021). In fact, Lean construction explicitly considers “people” as a main element for the transformation culture that it promotes (Hamzeh et al. 2021). Several studies in the domain of Lean construction have integrated the human touch into their objectives, means, or concepts. However, this touch could pertain to interrelationships, partnerships, physical abilities, cognitive abilities, or more. One approach to this concept is the investigation and analysis of construction workers’ physical and cognitive abilities through digital technologies. Barbosa and Costa (2021) identified and analyzed the commonly used methods for measuring, analyzing, and improving construction productivity using digital technologies. Such technologies were

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classified into several categories, including vision-based technologies, sensor-based technologies, and audio-based technologies. Perhaps sensor-based technologies allow for the most intricate exploration of the “people”, while still maintaining a non-invasive approach and healthy boundaries. A search for the term “sensor” on IGLC.net only results in seven studies; three of which refer to location sensors such as GPS and RFID technologies, two refer to visual management sensory aids, and one refers to the sensors that a human uses to capture stimuli in an environment as part of a biological mechanism. Only one study by Barbosa and Costa (2021) is related to wearable sensors for physiological measurements. While we might not be there yet in terms of exploiting the potentials of wearable sensors for physiological measurements in Lean construction research, the potentials of revolutionizing this field by intertwining Lean construction and wearable sensors – two independently powerful fields - is promising.

Therefore, this paper conceptualizes on sensor-based technologies in construction by conducting a conceptual walkthrough among extant studies utilizing wearable sensors for physiological measurements in construction and exploring potentials for exploiting Lean principles in this domain. Its objective is to provide research on wearable sensors in construction with a new insight through bridging extant research attempts in this domain to Lean concepts. In addition to embedding Lean concepts into previous studies, Lean theories and the perks that they provide are suggested to further refine future attempts. In this regard, several research questions are put forward and answered: (RQ1) What are wearable sensors and their usages? (RQ2) What studies employed wearable sensors in construction and what were their objectives? (RQ3) Which of the identified studies fall directly under the umbrella of Lean construction? and (RQ4) Which of the identified studies have objectives that fall under Lean construction goals?

This approach is established based on a distinction between two theories: Lean construction and the use of wearable sensors in construction. According to Lukka and Vinnari (2014), there are two types of theories: a domain theory and a method theory. A domain theory is a set of knowledge in an area of study with particular theories and constructs, while a method theory provides new insights into the domain theory to expand or offer an alternative explanation of its concepts. They also note that this distinction between the two theories is rather relative than absolute, and a theory may either be a domain or method theory depending on its role in the paper (Lukka and Vinnari 2014). As the scope of this study is to introduce Lean construction principles and tools as a novel perspective to the research on wearable sensors in construction, wearable sensors in construction are the domain theory that will be analyzed and have its concepts and applications re-evaluated through the method theory, Lean construction.

In the absence of studies utilizing wearable sensors in the context of Lean construction, this study contributes to the body of knowledge by proposing a new perspective to wearable sensor applications and possibly inspiring future research that bridges the two concepts. The paper starts off with a review on Lean construction principles, followed by a definition and classification of wearable sensors for physiological measurements, and a review on studies utilizing wearable sensors in construction. Finally, a bridging attempt between wearable sensors and Lean concepts is carried out. Final conclusions and future research recommendations are eventually proposed.

METHODOLOGY

As this conceptual paper aims to bridge existing theories in two separate contexts, the research methodology followed is theory adaptation. Theory adaptation papers “introduce alternative frames of reference to propose a novel perspective on an extant conceptualization” (Jaakkola 2020). The first step in theory adaptation papers is problematizing a particular concept (domain theory), followed by suggesting some perspective shifts to align the concept to its purpose by drawing from another theory (method theory) that is befitting to guide this shift (Jaakkola 2020).

Having already defined wearable sensors as the domain theory and Lean construction as the method theory of this study, wearable sensors in construction are investigated, and Lean concepts, principles, and tools are suggested to provide a perspective shift to wearable sensor applications. For this purpose, Lean construction principles and tools are discussed to establish a clear basis for the method theory. However, since the objective of this study is to correlate wearable sensors applications in construction to Lean construction, a thorough discussion of Lean construction principles will not be carried out. Instead, a cross-sectional approach will be adopted in an effort to provide a bird's-eye view of Lean construction. Afterwards, wearable sensors in general are introduced by defining and categorizing them. Research on wearable sensors in construction is then reviewed to provide better understanding of this domain theory in the context of construction. To conduct this review, keywords such as "sensor", "physiological measurement", "wearable", "EEG", "heart rate", "EDA", "eye movement", and "breathing rate" were searched for in databases from Google scholar and IGLC.net. Finally, Lean construction principles are used to propose a novel perspective on wearable sensors and their applications, in hopes of stimulating innovative future research for bridging the two theories.

LEAN CONSTRUCTION PRINCIPLES AND TOOLS

A study by Mossman (2018) aimed at answering the question "what is Lean construction?" and compiled results from previous presentations, research papers, and survey responses. One of the definitions described Lean construction as "an application to construction of a management ***philosophy*** defined by the ***ideal*** it pursues, the ***principles*** followed in pursuit of the ideal, and the ***methods*** used to implement the principles." Therefore, perhaps a good start for describing Lean construction without diving into trying to philosophize the ***ideal*** is through the 14 ***principles*** of the Toyota Production System elucidated by Liker (2004). Liker developed the "4P" model that divides the 14 principles into four categories: Philosophy, Process, People and Partners, and Problem Solving as shown in Figure 1. It is worth noting that the 4P model takes the shape of a pyramid, which implies that the foundation of the 14 principles is understanding and embracing the "Philosophy" and that the journey of adopting the principles is rounded off by a successful and perpetual approach of "Problem Solving".

Another famous concept in Lean is its approach towards eliminating three types of waste: Muri (overburden), Mura (unevenness or inconsistency), and Muda (waste) (Hamzeh 2009). Muri entails driving humans (or equipment) beyond their natural thresholds and can lead to safety issues and quality problems. It may be mitigated by ensuring proper process and resource planning (Hamzeh 2009). Mura in workforce (or materials) occurs in response to fluctuations in the process resulting from various factors such as unbalanced loads and highly variable demand (Hamzeh 2009). Muda may be identified as any element that increases cost in the absence of value creation, including workers waiting, unnecessary movement, unused employee talent, "making-do" or starting an activity before it is ready, and so on (Hamzeh 2009).

Moving forward with the elucidated principles, some of the Lean ***methods*** that offer process improvement and waste elimination include Bottleneck Identification and Analysis (BIA), Value Stream Mapping (VSM), Error Proofing (Poka-yoke), and Root Cause Analysis (RCA). In any system, the bottleneck is the subsystem that forms a point of congestion and limits the capacity of any system because of having lower efficiency than other subsystems. This renders the bottleneck the main determinant of the capacity of the system. Bottleneck identification provides the prospect of improving the process after pinpointing its source of impediment, and bottleneck analysis allows improving the system by analyzing the reasons behind the identified low throughput and drawing recommendations for improving its efficiency. An enabler for bottleneck identification and analysis is VSM, where all process steps necessary to transform raw materials into a completed product are visualized as a collection of value adding and non-value adding activities linked together (Liker 2004). VSM provides leeway to eliminate bottlenecks and wastes and to increase process flow and value. One way to minimize human errors in any process is "Poka-yoke" or error proofing, which refers to creative measures adopted to prevent errors committed by workers (Liker 2004). Liker (2004) also suggested that the 6th principle of the Toyota Way (standardized work) is a poka-yoke measure as it pertains to tailoring and continuously updating the "standard work chart" to incorporate error-proofing measures. Another view could be the learning curve associated with standardized work, which in turn could minimize errors among workers through unconscious execution of repetitive and previously verified procedures. Finally, RCA fosters searching for the root cause of problems rather than the source, as the root cause often lies beyond the source (Liker 2004). Toyota's problem solving process includes perceiving the initial problem, clarifying it, locating the point of cause, performing root cause analysis, implementing countermeasures, evaluating them, and finally standardizing the process (Liker 2004). Root causes for inefficiencies in a process could go beyond equipment or materials, as human factors could play significant roles in this aspect.

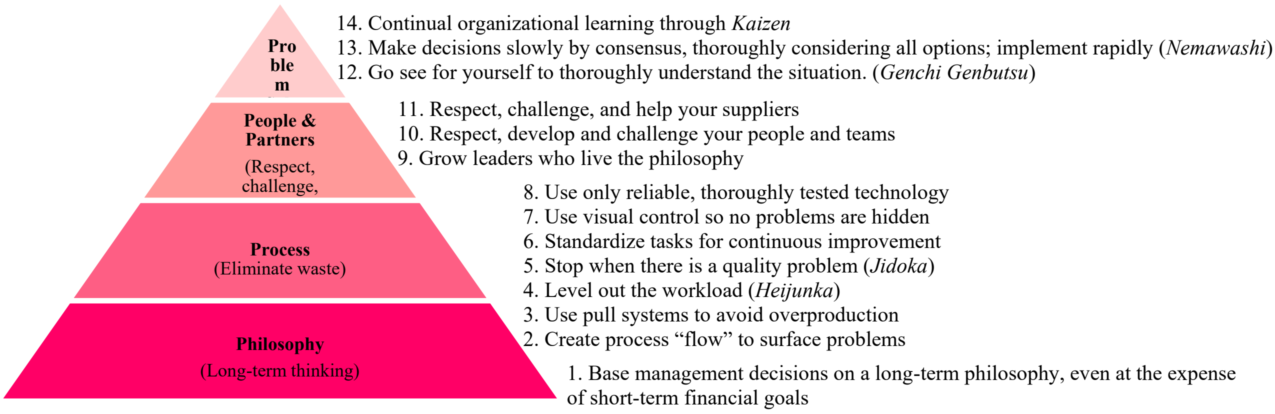

Figure 1: The "4P" Model of the Toyota Way (Liker 2004)

WEARABLE SENSORS FOR PHYSIOLOGICAL MEASUREMENTS

The advancements in wearable technologies have enabled the introduction of real-time wireless sensors for physical and physiological measurements into various industries including healthcare, sports, manufacturing, and construction. Wearable sensors for physiological measurements vary in terms device size, point of application, subject body part, and target measurement. A discussion of the available wearable sensors is carried out to classify the different sensors into categories pertaining to target body parts and target measurements.

Starting with the brain of the human body, electroencephalogram (EEG) devices are used to collect electrical signals created by the activity of neurons near the surface of the brain (Giannakakis et al. 2019). They measure the electrical current fluctuations between the EEG sensor electrode and the skin and amplify these fluctuations before performing any necessary filtering. EEG headsets are available in wired and wireless options and require a consistent electrical connection between the scalp of the subject and the electrodes (Giannakakis et al. 2019). Research has shown that EEG measurements are considered a reliable indicator of mental stress, fatigue, arousal, or psycho-emotional states. Moving to the eyes, eye-tracking sensors are typically used to measure blink counts, eye fixation times and counts, and pupil diameter. Eye blink rate has been analyzed and used by researchers as an indicator of stress in humans, while fixations are the time periods between eye movements when the eye stops at a specific position, and they reflect gazing on an object of interest and can be used to indicate situational awareness or stress. Pupil diameter was proven to indicate processing load and mental effort being exerted by the subject. Eye-tracking has generally been used by researchers in various domains such as risk perception (Hasanzadeh et al. 2017a) and human-computer interaction (HCI).

Heart measurements are arguably some of the most commonly collected measurements, and they include measuring the heart rate, the electrical activity of the heart through electrocardiogram (ECG) devices, and the volumetric change of the blood in the heart through photoplethysmogram (PPG) devices. Heart rate is the number of heart beats per minute, and it is used as an estimate of levels of stress (Giannakakis et al. 2019). Heart rate variability is another measure that is the distribution of the RR interval (interval between consecutive heart beats), and it is considered a valid indicator for stress. ECG, on the other hand, is the signal of the electrical activity manifesting in the heart's contractile activity (Giannakakis et al. 2019) and has been linked to stress in various studies. Finally, PPG is a non-invasive technique used to monitor changes in the blood flow in the cardiovascular system. It is based on illuminating tissues with a specific wavelength and measuring the reflected light (Banerjee et al. 2017). It has also been used to evaluate stress among subjects (Giannakakis et al. 2019).

Another vital component of the human body is the lungs, from which respiration or breathing rate may be measured. Respiration is the rate or volume at which humans exchange air through the lungs. Changes of respiration are observed with changes in the subject's emotional states, where respiration increases with emotional arousal, decreases with relaxation, and undergoes momentary interruption with tense situations (Giannakakis et al. 2019).

When it comes to limbs, movements and muscle electrical activity have been perceived as two significant measures that can help indicate psychological states among subjects. Limb movements are classified into upper and lower body movements, with upper body movements being positively linked to stress levels (Giannakakis et al. 2019), while lower body movements being linked to subjects' safety behavior due to their cyclic nature (Sun et al. 2020). Inertial Measurement Unit (IMU) sensors or motion suits track body motion by being attached to the subject's body. They have been used for various purposes including workers' safety and level of exertion (Ryu et al. 2020). Muscle electrical activity, on the other hand, is measure using electromyogram (EMG) devices. EMG devices measure a muscle's myoelectric activity to assess physical loads acting on a muscle. They are commonly used to evaluate the causes and potential interventions for work-related musculoskeletal disorders (Al-Qaisi et al. 2021).

Finally, the human body's largest organ, i.e., the skin, has also been a target for researchers attempting to identify stress among subjects by measuring the skin temperature and the electrodermal activity (EDA). Generally, variations in the temperature of the skin have been associated with anxiety and stress conditions and are measured at different body parts, such as the finger, face, or arms. EDA is the measurement of the electrical flow through the skin surface and has been extensively linked to stress measurement (Giannakakis et al. 2019).

WEARABLE SENSORS IN CONSTRUCTION RESEARCH

Construction research has been successful in adopting real-time measurement of physiological factors among construction workers using wearable sensors. Such adoptions vary in terms of target measurement, used sensor, human factor, and study objective. Table 1 represents a summary of a review of studies that have adopted this approach in the construction industry. For each study shown in Table 1, the target measurement and the sensor used to measure it are shown, in addition to the human factor that was investigated in the study in terms of measurement, prediction, or detection. Table 2 shows the objectives of the identified studies.

Table 1: Summary of Select Studies Employing Physiological Sensors in Construction

Study	Target Measurement	Sensor	Human Factor
(Al Jassmi et al. 2019)	1a. Respiration rate 1b. Heart rate	1a. Heartrate monitor 1b. Breathing rate	Happiness

	2a. Blood volume pulse 2b. Skin electrical properties 2c. Skin temperature	monitor 2a. PPG 2b. EDA 2c. Thermopile	
(Anwer et al. 2021)	1a. Heartrate 1b. Breathing rate 1c. Skin temperature 2. Skin Temperature 3. Heartrate	1a. Heartrate monitor 1b. Breathing rate monitor 1c. Temperature sensor 2. PPG 3. Heartrate monitor	Fatigue
(Aryal et al. 2017)	1. Changes in the heart rate 2a. Brainwave signals frequencies 2b. Thermoregulatory changes	1. Heart rate monitor 2a. EEG 2b. Thermopile	Fatigue
(Chen et al. 2017)	Brain electrical activity	EEG	Mental workload
(Choi et al. 2019)	Skin temperature	EDA	Risk perception
(Dzeng et al. 2016)	Eye movement	Eye tracking sensor	Hazard identification
(Hasanzadeh et al. 2016)	Eye movement	Eye tracking sensor	Situational awareness
(Hasanzadeh et al. 2017a)	Eye movement	Eye tracking sensor	Hazard identification
(Hasanzadeh et al. 2017b)	Eye movement	Eye tracking sensor	Safety knowledge
(Hwang et al. 2018)	Electrical activity of the brain	EEG	Emotional State
(Jebelli et al. 2018)	Electrical activity of the brain	EEG	Stress
(Jebelli et al. 2019)	1. Heart volumetric change 2. Electrical properties of the skin 3. Skin temperature	1. PPG 2. EDA 3. Thermopile	Stress
(Lee et al. 2021)	1. Heart volumetric change 2. Skin electrical properties 3. Skin temperature	1. PPG 2. EDA 3. Thermopile	Risk perception
(Lee et al. 2017)	1. Heart electrical output 2. Energy expenditure - physical activity levels - sleep quality	1. ECG 2. Accelerometer	Physical responses, health statuses, and safety behaviors
(Plarre et al. 2011)	1a. Heart electrical output 1b. Skin conductance 2. Skin temperature 3. Ambient temperature 4. Body motion data 5. Relative lung volume at rib cage	1. ECG 2. Skin temperature 3. Ambient temperature 4. Accelerometer 5. PPG	Stress
(Ryu et al. 2020)	Whole-body motion data	Accelerometer, gyroscope, magnetometer	Productivity & Safety
(Sun et al. 2020)	Leg movement	Accelerometer, gyroscope, magnetometer	Risk perception
(Umer et al. 2020)	1a. Respiration 1b. Heart electrical output 1c. Skin temperature	1a. Respiration sensor 1b. ECG 1c. Thermopile	Fatigue
(Wang et al. 2019)	Brain electrical activity	EEG	Risk perception
(Wijsman et al. 2011)	1a. Heart electrical output 1b. Respiration 2. Skin conductance 3. Muscle activity	1a. ECG 1b. Respiration sensor 2. EDA 3. EMG	Stress

Table 2: Objectives of Select Studies Using Physiological Sensors in Construction

Study	Objective
(Al Jassmi et al. 2019)	To assess the ability of capturing the effect of construction workers' happiness on their productivity using physiological signals.
(Anwer et al. 2021)	To establish absolute and relative reliability of textile-based wearable sensors to monitor physical fatigue during bar bending and fixing construction tasks.
(Aryal et al. 2017)	To show that physical fatigue in construction workers can be monitored in real time using wearable sensors.
(Chen et al. 2017)	To measure task mental load using EEG and explore the possibility of assessing the cognitive/mental workload of construction tasks through EEG
(Choi et al. 2019)	To show the feasibility of using wearable sensors to understand workers' perceived risk in construction sites continuously.
(Dzeng et al. 2016)	To compare the search patterns of the experienced and novice workers using an eye-tracker by creating a digital building construction site and designing a hazard-identification experiment involving four workplaces featuring obvious and unobvious hazards (e.g., falls, collapses, and electric shocks
(Hasanzadeh et al. 2016)	(1) To identify workers with lower situational awareness (SA) and pinpoint opportunities to provide proactive training and develop guidelines for workers that will reduce human error and accidents; (2) To measure the same workers' SA level after training to determine if their SA improved
(Hasanzadeh et al. 2017a)	To provide a proof of concept that certain eye movement metrics are predictive indicators of human error due to attentional failure and use these findings to identify at-risk construction workers, pinpoint required safety training, measure training effectiveness, and improve future personal protective equipment.
(Hasanzadeh et al. 2017b)	To demonstrate the potential application of eye-tracking technology in studying the attentional allocation of construction workers and to show that eye tracking can be used to improve worker training and preparedness.
(Hwang et al. 2018)	To investigate the feasibility of measuring workers' emotions in the field using a wearable EEG sensor.
(Jebelli et al. 2018)	To improve workers' safety, health, wellbeing, and productivity through the early detection of workers' stress
(Jebelli et al. 2019)	To enhance workers' health, safety, and productivity through early detection of occupational stressors on actual sites.
(Lee et al. 2021)	To provide a new means of automatic, continuous, objective, and non-invasive method for monitoring construction workers' perceived levels of risk
(Lee et al. 2017)	To examine the reliability and usability of wearable sensors for monitoring roofing workers' on-duty and off-duty physiological status and activities.
(Plarre et al. 2011)	To propose, train, and test two models for continuous prediction of stress from physiological measurements captured by unobtrusive, wearable sensors and provide the first classifier of stress that can be readily used in natural environments without pre-calibration
(Ryu et al. 2020)	To provide an in-depth understanding of the linkage between body loads, work experience, techniques, and productivity.
(Sun et al. 2020)	To demonstrate the potential of using wearable sensors to identify workers with personality traits associated with unsafe behavior.
(Umer et al. 2020)	To highlight the advantages of using combined cardiorespiratory and thermoregulatory measures to enhance modelling physical exertion using machine learning algorithms.
(Wang et al. 2019)	To propose a new hybrid kinematic-EEG data type and adopt wavelet packet decomposition to compute the vigilance (risk perception) measurement indices with the

	redefined EEG sub-bands.
(Wijsman et al. 2011)	To detect mental stress by measuring physiological signals using a wearable sensor system

WEARABLE SENSORS FROM A LEAN CONSTRUCTION PERSPECTIVE

It is rather evident that all of the mentioned studies do not bear on Lean construction in terms of directly stated objectives or methods. A search for the terms “Lean”, “Kaizen”, “Toyota”. “Value Stream”, “Root Cause”, “Bottleneck”, or “Proofing” gives back zero results. An inspection of the stated objectives and methods also verifies the lack of link between the studies and Lean.

Liker (2004) referred to “Lean Company X” that claimed to be Lean but ended up being in need for radical improvements to attain the “Lean” attribute. On the other hand, a company can foster the same principles that Lean promotes and employ the same methods and techniques for improvement and control as those adopted by Lean but not identify as a “Lean” company. An analogy between the given example and the current situation of research on wearable sensors in construction and their remoteness from Lean may be drawn. Despite not being referred to as studies in the field of Lean construction, all of the mentioned studies hold Lean principles and goals, such as enhancing safety and the wellbeing of workers, improving productivity, and matching the load to the capacity of the workforce. To further reinforce this view, a bridging attempt between the studies and Lean principles and methods is carried out. In this attempt, every Toyota Principle addressed in each of the identified studies is listed. Additionally, each type of waste among the three wastes identified in Lean (Muda-Mura-Muri) that the studies attempt to eliminate is also listed. Finally, for each study, the Lean tool or technique that may complement the study’s objectives is identified.

All of the identified studies mentioned in Table 1 were found to address Toyota’s principles 1, 5, 8, 12, and 14. Principle 1 calls for basing decisions on long-term philosophies, even at the expense of short-term financial goals. As all studies utilize wearable physiological sensors, it is no secret that some financial compromise is expected from organizations that are willing to invest in some wearable sensors or collaborations with other organizations offering services in this area. However, such investments guarantee financial gain from productivity improvements among construction workers, as all studies have successfully proven a direct negative relationship between physical fatigue and productivity. Principle 5 promotes building a culture of stopping to fix problems. By analyzing physiological measurements and deducing productivity and safety performance, organizations are enforcing a culture of direct intervention when workers’ physiological statuses indicate unsatisfactory conditions. This would not only enhance the workers’ safety and wellbeing, but also improve their productivity and the overall project performance. As for principle 8 calling for using reliable technologies that serve the people, all studies employ verified sensors whose primary goal is to serve the mental and physical wellbeing of the workers. Regarding principle 12, it encourages organizations to monitor the process closely and personally, and what better way could this concept be implemented other than by collecting and analyzing the workers’ physiological and psychological statuses to ensure their mental wellbeing and physical safety are maintained? Finally, principle 14 entails maintaining a culture of continuous learning and improvement or “Kaizen”. By “zooming into the minds and bodies of construction workers” which are in daily variation, we would be instilling the belief that continuous monitoring and learning about the workers’ physiological and psychological statuses are essential for improving the performance of the project, leading to a notion of continuous improvement among all organization members.

Studies addressing risk perception based on eye movements touch on principle 7, which promotes using visual controls to unhide all problems in the process. This link is established through the studies' aim to track eye movements to monitor if and how safety hazards are detected by the subjects. By doing so, they are fostering the importance of visual control in detecting and unhiding risks that may face workers while performing their work.

When it comes to how the selected studies attempt to eliminate any of the three wastes through their objectives, Muda, which is any kind of waste in the process including inefficiency in the workers' efforts, may be considered a prevalent target among all studies. Fundamentally, all of the included studies have one common vision: enhancing construction workers' productivity; some achieve this goal by focusing on stress, mental load, or emotional state, while others achieve it by focusing on physical fatigue or risk perception. When it comes to Muri, or overburden, if perceived from a human-oriented lens, it directly signifies physical or mental overload. For example, studies addressing physical exertion or fatigue may be linked to Muri in terms of their approach to matching task physical loads to the workers' physical capacities, from which their study objectives originated. This also applies to studies addressing mental stress, which arise from tasks' mental loads overpowering workers' mental capacities. Finally, Mura, or unevenness, is mainly manifested in studies that also exhibit Muri-elimination approaches. In fact, Muri is often described as overburden resulting from Mura, which further reinforces this concept. Table 3 summarizes the human factors and the sensors that can be used to identify them and maps them with the discussed Lean concepts in order to visualize the embedded links between the two topics.

Table 3: Mapping of Human Factors, Sensors, and Lean Concepts

Human Factor	Sensor	P1	P5	P7	P8	P12	P14	Muda	Muri	Mura
Stress & Mental Workload	PPG – EDA – EEG – ECG – EMG - skin temperature - ambient temperature – accelerometer - respiration sensor	X	X		X	X	X	X	X	X
Safety & Risk perception	EEG - EDA – PPG - accelerometer - thermopile - eye tracking sensor	X	X	X	X	X	X	X		
Fatigue	EEG - ECG – PPG – thermopile - breathing rate monitor -heart rate monitor	X	X		X	X	X	X	X	X
Happiness	PPG – EDA – thermopile - heartrate monitor - breathing rate monitor	X	X		X	X	X	X		

INSIGHTS AND GAPS

So far, means of utilizing wearable sensors for physiological measurements have been analyzed from the perspective of their potential to revolutionize the area of Lean construction by providing valuable insights into workers' physiological and psychological statuses on the jobsite. However, by switching the lens to analyzing how Lean construction can complement research advancements employing wearable sensors, some key areas where more research is needed to optimize wearable sensor applications in construction are identified. For example, the **standardization of physiological measurements** is vital for ensuring the viability of this approach. Currently, there is no standardization of the type of physiological measurements that should be collected or the method of data collection, which can complicate the comparison of the results between studies and drawing meaningful conclusions. As a major promoter for standardization, Lean construction can help address this limitation by providing guidelines for the measurement and collection processes. In fact, in the discussion of the 6th Toyota principle, Liker (2004) states that "today's standardization is the foundation on which tomorrow's improvement will be built". By standardizing (1) the set of sensors to be used collectively and (2) the method of data collection based on verified studies and analyses, a reliable standard for similar studies adopting this approach can be developed. Another concern is the **integration of wearable sensors into construction workflows**, such as how to minimize disruption to work processes, how to manage the data collected, and how to ensure that the sensors are used consistently and effectively. Many studies in Lean construction have addressed measuring and optimizing workflow in terms of value, labor movement, and design. Such approaches may be adopted to tackle this limitation in the integration process of wearable sensors with Lean construction. Above all, **ethical and humane considerations** such as sustaining the human touch, privacy, and the use of the data for performance management represent additional concerns. With Lean construction's notion towards a human-centric approach in construction 4.0 technologies, unconscious consumption of technological advancements that may backfire and corrupt the construction industry is resisted (Noueihed and Hamzeh 2022). Attempts to demarcate the expansion of technology and its uses in construction are constantly being evoked within the Lean construction community, which can address the concerns around disregarding the ethical aspect of employing wearable sensors in the industry.

CONCLUSION

Most studies using wearable sensors in construction identified their objectives and means from a general productivity or safety standpoint. However, further meta-analysis brings uncovered relationships between these studies and Lean construction to light. This study relates wearable sensors in construction to Lean principles as an initiative to bring about innovative research approaches in this domain. Upon exploring some Lean concepts such as Toyota's 14 principles and the three types of waste, evident links between them and the objectives of existing studies on wearable sensors can be drawn. Results showed that all of the identified studies specified objectives that directly pertain to five of Toyota's principles, while some studies specified objectives that pertain to one additional Toyota principle. Additionally, Muda was a common target among all identified studies to be eliminated, while Muri and Mura were a common target among those pertaining to mental and physical workloads. This conclusion addresses this study's fourth research question as to which of the identified studies have objectives that fall under Lean construction goals. From a different standpoint, a brief analysis on how Lean construction can help foster the utilization of wearable sensors in construction is presented.

This study sets a cornerstone for future research that could use the advancements provided by wearable sensors and put them into use from a Lean construction perspective. Future research could develop conceptual models or frameworks for the use of wearable sensors in a Lean context by systematically specifying steps and measures to be applied for successful implementations. Future studies could also highlight the challenges and opportunities that come with the implementation of wearable sensors in Lean construction, including issues of data privacy, accuracy, and compatibility. Furthermore, from an opposite perspective, wearable sensors can help enhance Lean construction research approach by providing real-time data, improving worker safety and productivity, and reducing waste and errors. Further analysis on this subject may be conducted to reinforce the built connection between the two topics.

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A CONSTRUCTION INFORMATION SYSTEM AS A LEAN INFORMATION MANAGEMENT ENABLER – CASE STUDY

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ABSTRACT

Information Management Systems, or just Information Systems (IS), are important platforms to manage processes with a large volume of information exchange, guaranteeing the appropriate flow of accurate information. In the Architecture, Engineering and Construction (AEC) industry, the use of information systems is still modest in contrast with the volume of data produced in the industry. However, with the advance of the digital transformation of Construction 4.0, this information gains even greater prominence and can be considered the most valuable asset during construction phases such as Pre-design, Design, and Procurement. Lean Information management is the application of lean thinking to information management, where the information can be considered a value and able to flow, removing waste, pull, and being in the process of continuous improvement. This paper presents an analysis of an Information Management System, ProNIC, intensively used and endorsed in Portuguese public construction contracts. Originally conceived to add value to the end-user (customer), the Portuguese Government, ProNIC is now being assessed as an enabler of lean processes in the management of construction information.

KEYWORDS

Information systems, lean construction, digitization, process, enabling lean

INTRODUCTION

Information is a critical resource for the efficiency of today's businesses, and their management systems are essential for the performance of organizations that depend on knowledge. Information management can be defined as the activities that involve the creation, presentation, organization, maintenance, visualization, reuse, sharing, communication, and disposal of

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information. Information can be considered as value, due to the way it is processed and flows to the end user through the exchange, sharing and collaboration procedures. (Hicks, 2007).

Lean information management (LIM) is a concept that links two well-established fields in the literature: Lean thinking and information management. The objective is to improve the flow of information by eliminating or reducing waste and non-value-added activities (Teixeira et al., 2019). Therefore, Information Management Systems, or just Information Systems (IS), are the key to treating information with proper value, managing it, and getting it flowing, with due relevance and at due time.

In AEC industry, data waste or inefficient flow can potentially causes loss of important information, rework due to missing or outdated information, delays due to waiting for information, and unnecessary processing of information, among other wastes (Ré & Teixeira, 2018; Tribelsky & Sacks, 2011). There are a large number of different IS that process business information, such as financial, payroll, customer relationship management (CRM), product data management (PDM), and inventory management systems (Hicks, 2007), However, a range of technical information is neglected by the more spread systems, such as design information, which requires specific treatment (Ahankoob et al., 2020).

ProNIC (Portuguese acronym for Construction Information Standardization Protocol) is a construction information system that manages specific information from the construction process (Sousa et al., 2012). The origin of ProNIC comes from the Portuguese Government awareness that there was a lack of standardization on construction projects at the bill of quantities level, as well as flaws at the specifications level supporting the design stage documents (Mêda, Calvetti, Ribeiro, et al., 2021) . Therefore, ProNIC was conceived from the perspective of client improvement, specifically the Portuguese Government. From this evaluation, it is possible to envision that ProNIC can act as a Lean Information Management enabler, even though it was not originally designed in this context.

The analysis of construction information from a lean perspective is necessary to recognize the function fulfilled by the IS themselves under managed information. Analyzing the performance of these systems under a lean vision will enable continuous improvement of the processes involved.

BACKGROUND INFORMATION

LEAN INFORMATION MANAGEMENT

Lean Manufacturing was developed from Toyota Production System (TPS) to increase the competitiveness of the automotive company (Womack & Jones, 1997).

Taiichi Ohno, a Toyota engineer and executive, started the TPS application, by identifying seven types of waste found in any process, and Womack & Jones (1997) added the eighth waste: **Transportation**; **Inventory**; **Motion**; **Waiting**; **Overprocessing**; **Overproduction**; **Defects**; **Underutilization of people**. To prevent, reduce, or eliminate the above-mentioned waste, five Lean principles have been defined, which are (Hicks, 2007; Womack & Jones, 1997): **Specify Value**; **Identify the Value Stream**; **Flow**; **Pull;** and **Pursue Perfection**.

These principles can also be applied to information flows. Ensuring that useful information is produced promptly and made available only to the right people at the right time is the goal of information management. However, waste in the context of information management is less clear and is generally not as visible (Hicks, 2007).

The waste in the context of information management is related to the downtime or additional activities that are a consequence of not providing the stakeholder with the necessary information with immediate access, in a simple, accurate and updated way. Like lean thinking in the manufacturing context, lean in information management is about identifying and enabling improvements in the flow of information, eliminating, or reducing waste in the various aspects of information management. The objective, as in manufacturing industries, is that these improvements are reflected in efficiency, productivity, overall process and product quality, also by allocating specialized human effort where value is added to the final product (Hicks, 2007). The waste associated with the information flow may include the effort necessary to overcome difficulties in retrieving or accessing information, or in activities that require the confirmation and the correction of inaccurate information. The principles that LIM considers are:

- the information should only be created if it is useful to decision-makers (add value).
- the information should only be sent to those who need them.
- the information should be quickly processed, preferably in real-time, avoiding waiting on the part of the users; and
- the information should be provided by sources without duplication of data.

So even though the concepts have originated in the field of production processes, it is possible to apply Lean principles to information flow processes. The following are examples of how Lean waste can be understood for information flow (Ré & Teixeira, 2018):

1. **Transportation**: consists of the unnecessary movement of information between various sources, manifesting itself, for example, in the re-insertion of information, due to incompatibility of systems or resistance in the use of IS.
2. **Inventory**: supplying more information than is necessary for decision-making at a given moment. In practice, it may also refer, for example, to information that although it exists, is not in the right place, conditioning the execution of certain activities due to lack of information.
3. **Motion**: consists of unnecessary steps to collect information that is not easily accessible.
4. **Waiting**: refers to the time it takes to obtain information, reflected in the time that a task or process cannot be carried out due to lack of information.
5. **Overprocessing**: related to the lack of information and the activities required to fill that lack, which may include the creation of new information or the identification of additional information.
6. **Overproduction**: all the effort devoted to identifying valuable information due to the high volume of existing information, much of it worthless.
7. **Defects**: consists of inaccurate, wrong, outdated, or incomplete information.
8. **Underutilization of people**: consists of the incorrect use of an organization's human resources, due to inadequacies in the processes or in the information itself.

PRONIC

ProNIC – Protocolo para a Normalização da Informação Técnica na Construção (Portuguese Construction Information Standardization Protocol) – is a computer platform initially developed in 2005 – 2008 to promote the standardization of technical contents for the construction of buildings and road works, supported by the Portuguese Government. It quickly grew in scope and functionality, allowing collaborative work, delivering high-quality Bill of Quantities (BoQ) from standardized, comprehensive work break-down structures (WBS), and possessing an organized document repository that could aggregate information throughout the construction process, including managing the monthly measurement reports of the construction phase, as well as producing a variety of indicators and metrics (Mêda, et al., 2021). It was also compliant with the newly launched CCP – Código dos Contratos Públicos (Public Procurement Code), and has been heavily used by Parque Escolar, EPE – a public company overseeing a very large, ongoing, high-school renovation campaign in Portugal (Mêda & Sousa, 2016).

ProNIC perform document collection, storage, management, and sharing functionalities that work exactly like a **Common Data Environment (CDE)**, even before this concept became widespread due to its use for BIM projects (Mêda, et al., 2021). A CDE is a central space for collecting, managing, evaluating, and sharing information. All stakeholders can obtain information and store their data concerning the project in a single environment. The CDE also allows the creation of models for coordination, partial models, databases, and documents for specific phases of the construction process. In addition, the CDE leads to a higher rate of information reuse, simplifies the aggregation of information models, and simultaneously serves as a central archive for documentation (Preidel et al., 2016).

Figure 1 summarizes the processes supported by ProNIC. For the project phases indicated, the listed stakeholders undertake the corresponding activities in the system, promoting the standardization of information throughout the process.

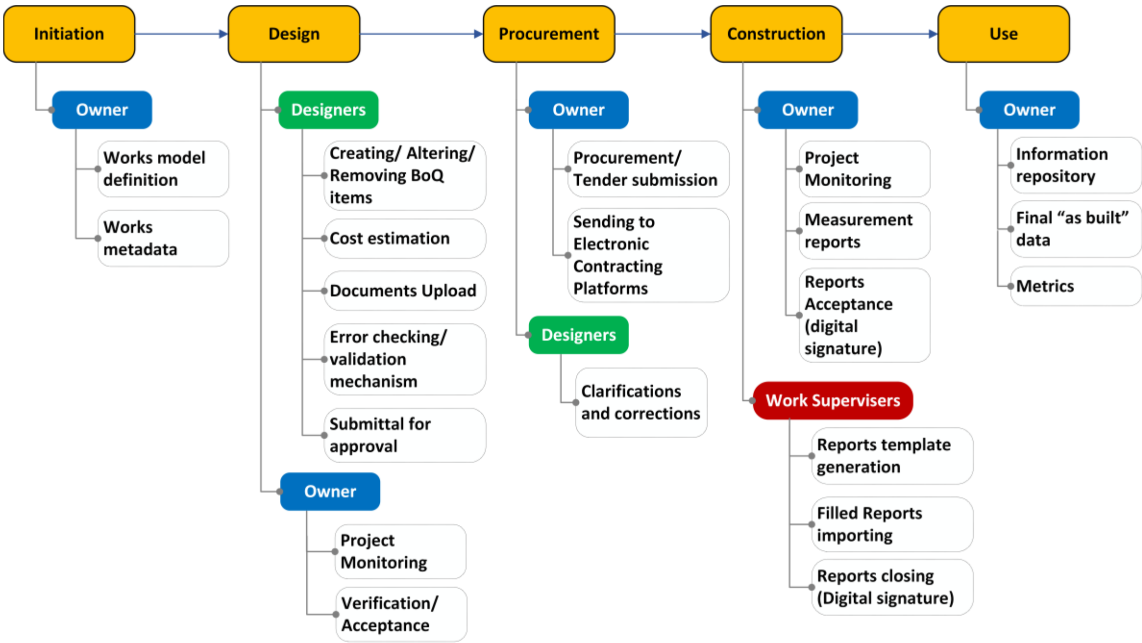

Figure 1: ProNIC Process Overview

Within the scope of the REV@CONSTRUCTION Mobilizer Program (https://revconstruction.pt/), aiming at accelerating the adoption of Construction 4.0 in Portugal, ProNIC is currently being updated: its IT platform is being redesigned and its technical contents are being revised, in order to prepare ProNIC for a new phase within Construction 4.0. New functionalities, such as integration and interoperability with BIM models, a cost database, new classifications tables related to the construction process, and BIM object libraries are being planned for future implementation (Mêda et al., 2016). This evolution is also being designed under a lean perspective to deliver continuous improvement not only in the System itself but also in the processes related to it.

METHODOLOGY AND RESEARCH QUESTIONS

This study grounds a critical analysis of construction project processes performed by different agents considering the support or not of information management platforms. The findings and intuitions are evaluated by facing the basic principles of lean and Lean Information Management. ProNIC is used as the case study to observe improvements in the processes, as shown in Figure 1: ProNIC Process Overviewin terms of information flow, work overload reduction, and suppression of activities not adding value.

The research is motivated to provide answers to the following questions: Can a construction Information System be a tool promoting Lean Information Management? What Lean thinking improvements has ProNIC implemented? How can the processes performed by ProNIC be further improved based on Lean Information Management?

FINDINGS

COMMON DATA ENVIRONMENT

The Common Data Environment feature plays a central role in the operation of ProNIC as an information manager. The research conducted found that, as a CDE, ProNIC follows Lean thinking in the aspects shown in Table 1.

Table 1: Lean Wastes and Benefits of ProNIC as a CDE

Lean Wastes	ProNIC Benefits
Transportation	A single "information container" where all files must be, eliminates the need for the same information to be addressed to all stakeholders.
Inventory	Organizing the files in a predefined directory structure makes it possible for a file to be available only in the right place, in the right version, avoiding being available in multiple versions and multiple locations.
Motion	According to the information above, simply organizing the files eliminates steps such as contacting the responsible parties to request information or confirming that the available version is the current one, for example.
Waiting	All current information is available to all necessary stakeholders at the time it is loaded into the system.
Overprocessing	Using the directory structure you can check the currently available version, and if in doubt you can avoid the trouble of checking and evaluating what is available, for example.
Overproduction	No effort is devoted to searching for valuable information among the vast amount of existing information, much of which is not important.
Defects	Only the current information is available. This is sufficient to ensure that no outdated versions can be used, preventing defects in subsequent processes.
Underutilization of people	The efforts expended for all information organization are usually skilled professionals' time spent on activities with low or no added value.

Therefore, the CDE provides gains in the entire ProNIC process under the Lean perspective. Schimanski et al., (2021) conclude that there was greater confidence in the reliability of the information used in a project when using a CDE workflow, including regarding the conjunction of Lean Construction techniques.

OWNER

The Portuguese government was the one that initially demanded to use ProNIC. Therefore, its functionalities were designed to improve the flow of information related to this specific client. However, only with the in-depth use of Parque Escolar, EPE, the Owner's current scope was defined, with all the phases and activities performed shown in Figure 2.

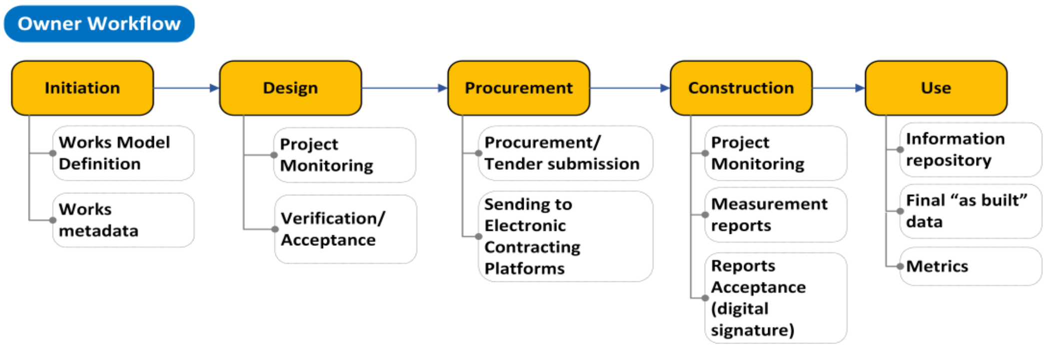

Figure 2: ProNIC Owner´s Workflow

The most relevant flows benefited were:

Works Model Definition/ Works metadata: The Owner defines the Work Model, with information such as Construction Type, Intervention Type, Construction Units, etc. This information is available to the project team at any time from the beginning of the process, avoiding delays in defining information, overproduction of elements with wrong data, and especially minimizing defects in the compatibility of disciplines.

Project Monitoring: In agreement with the CDE definitions, the necessary information for monitoring is always available in its current version, avoiding waiting, searching for information, confirmation of versions, and updates.

Verification/ Acceptance: The confirmation of the reception of the projects, properly formatted to meet the legal requirements, guarantees that the process will only move forward with all the necessary information, avoiding the production of elements not needed at the moment, eliminating the need to search for these projects, move them, store them in intermediate directories, reducing the work of the specialized team with non-technical functions.

Procurement/Tender submission/ Sending to Electronic Contracting Platforms: Like the reception and fulfillment of legal requirements, the tender submission and sending to the contracting platforms benefits from the organization of pre-determined files facilitating the management of the information needed for submission.

Construction Management: The automatic emission of the measurement reports for those involved in the process (Contractor, Supervision, and Owner) avoids divergence in the information, simultaneous verification, and promotes compliance with legal limits regarding modifications of the contract and other legal requirements.

In terms of Lean Wastes, Table 2 shows a summary of the benefits of ProNIC to the Owner.

Table 2: Lean Wastes and Benefits of ProNIC to the Owner

Lean Wastes	ProNIC Benefits
Transportation	Taking advantage of ProNIC's CDE role, the information needed for legal purposes is organized in its respective directories as soon as the appropriate versions for these uses are available, with no need for movement between directories.
Inventory	Once again, the CDE role allows the elimination of intermediate directories to organize files for submission to platforms, provisioning, validation, and other legal provisions.
Motion	The ease of access to information by the owner, with directories organized for the proper uses, avoids unnecessary steps for collecting the correct information.
Waiting	The request for information is one of the primary causes of waiting. Immediate access to all current information by the owner eliminates this wait.
Overprocessing	The predefined structure of the documentation directs the need to create files

	with only the information needed for the procedure at hand.
Overproduction	There is no need to search for information needed for procedures.
Defects	The owner can monitor the entire process, have access to intermediate versions, control demands, and pull production enabling a correct flow of information, without defects, outdatedness, or incompleteness.
Underutilization of people	The team allocated by the owner for process monitoring oversees technical and management checks, releasing them from the role of mere file organization.

In conclusion, the owner mainly benefits from ProNIC's CDE functionality to achieve a better flow of information. It is worth noting also that the workload at the end of the processes for preparing files and information for tender no longer exists with the automation provided by ProNIC.

WORK SUPERVISORS

The role of the work supervisors in the execution of Portuguese public contracts is linked to the owner, and consequently, the activities performed regarding measurement reports are related to the owner's project monitoring activities. Therefore, the analysis made above for the owner, concerning construction management, can be equally replicated for the supervisors.

DESIGN TEAM

Since a traditional AEC design project contains two major groups of documents, Drawings, which provide a complete visual representation of the final product, and Specifications which are essential for the proper understanding and execution of the Drawings by providing technical specifications, Bill of Quantities (BoQ), material and equipment lists, detailed measurements, and construction/functional descriptions, ProNIC assists in the management of both (Ribeiro et al., 2022).

For the drawings, ProNIC's CDE feature promotes the benefits previously discussed in the specific section of this paper. For specifications, ProNIC stands out in its role with the design team for the creation of the Standardized Bill of Quantities. Although these two facets of the same design project are interdependent by nature, they tend to have incompatibilities due to the segmentation into numerous design disciplines involved, the types of documents created, and the separate production of these documents (Ribeiro et al., 2022). Digitization, on its own, can facilitate how the different elements of design information are related, however, for it to be effective it requires standardized and interoperable information structures (Mêda et al., 2022).

Therefore, ProNIC's role in producing the design specifications begins by providing a Work Breakdown Structure - Construction Works (WBS-CW) with the appropriate parameters that differentiate the items and that influence the activities' price. This serves as the basis for the creation of the Standardized BoQ. At the end of the process, the validation work has partially been done during the process by performing error checking, and the consolidation between all project disciplines, which tends to be time-consuming and error-prone, is automatically performed by ProNIC.

It is for this reason that ProNIC came to have immense importance in the designers' work, even though it is summarized in the overview presented in Figure 3.

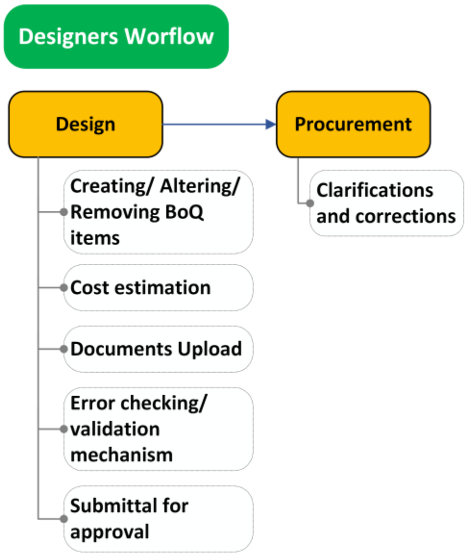

Figure 3: ProNIC Designers overview

However, despite the summary presented, the interaction between ProNIC and the design teams is more intense and can be best represented by the flowchart in Figure 4.

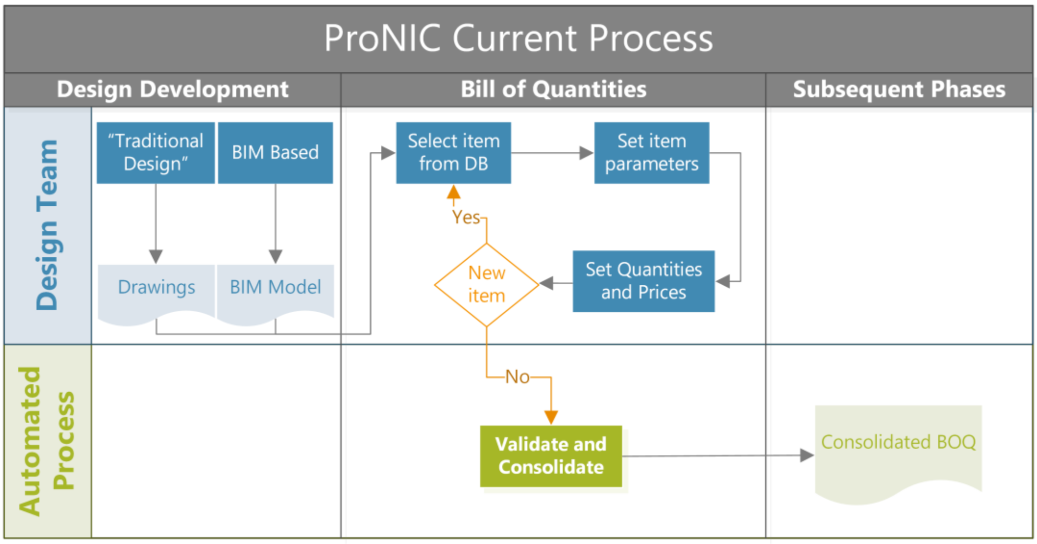

Figure 4: ProNIC designer changes process

Thus, standard BoQ creation in the current ProNIC process is independent of the chosen design method, whether "traditional" or BIM. The design team does most of the work, while ProNIC combines the BoQs from each design discipline to create the consolidated BoQ. The flow of creating a BoQ item is therefore repeated for the totality of items. The predefined WBS-CW items and parameters assist the design team in using complete, correct, and up-to-date design information, and error checking, in addition to the digital signatures and document uploads present at the end of the process. Cost estimating and quantification are also inputs to be filled by the design team.

Therefore, the flow between the design team and ProNIC proves to be one of the most intense, frequent, and repetitive in this process. It is in this perspective that it is possible to verify the advantages achieved in this flow from a lean information management approach:

Creating/ Altering/ Removing BoQ items: This is the main interaction flow between ProNIC and the design team. Therefore, the action takes place from obtaining the Works definition, set by the owner, to the validation and consolidation of the BoQ from all project disciplines, to allow the creation of the Standardized BoQ.

However, the largest share in the significance of information exchanged between ProNIC and the design team is due to the use of WBS-CW, which directs designers to standard information, with items, parameters, options for filling in the parameters, measurement units, all standardized and technically aligned, avoiding erroneous, incomplete, duplicated, or missing information.

Cost estimation: With BoQ standardization, ProNIC allows the project team to have a cost database for comparison at the item level. This comparison is not direct and demands coordination by the team, however, the information is available for use.

Documents Upload: The CDE function along with automatic validation, and error checking, allows the design team to be aware of which documents should be uploaded at the appropriate stages of the process, enables validation by the owner and other stakeholders involved in this process, and that the available versions are always the current ones.

Error checking/ validation mechanism: Occurs simultaneously with the creation of the BoQ, indicating existing items, and creating the consolidated Bill of Quantities.

Submittal for approval: Design team document's final validation. Only from this submission, the information can be considered able to be used in the following process.

The benefits of ProNIC to the Designers regarding Lean Wastes are shown in Table 3.

Table 3: Lean Wastes and Benefits of ProNIC to the Design Team

Lean Wastes	ProNIC Benefits
Transportation	A major gain in face of the number of people involved in this phase of the process inputting information in a unique document. Avoids constant requests and exchange of different versions of the information.
Inventory	Uses the CDE function to organize data to avoid multiple directories and files with the same information.
Motion	Again, due to the CDE function, it eliminates all the need to search for information in different places and with different actors in the process.
Waiting	Automatic error checking at the moment the item is created in the BoQ, without the need to request information. It allows the creation of immediate partial versions of the BoQ, allowing the checking of the process' progress. Submission and immediate availability at the end of the work.
Overprocessing	The creation of intermediate BoQs is a necessity for the proper monitoring of the process, but it demands almost an identical amount of work as the definitive one. This process automation is already an immense gain of information overprocessing for the design team.
Overproduction	CDE allows avoiding the production of unnecessary information at the moment and the immediate identification of current information.
Defects	The biggest gain and the goal of using the system. The standardized information, from previous phases prescribed by the owner to the consolidation with error checking at various moments, allows the creation of construction documentation to be a process with a much-reduced error occurrence.
Underutilization of people	The design team stays fully focused on value-adding activities, especially in the consolidation phase, which tends to be a high-volume phase.

In conclusion, once again the CDE feature plays an important role in this interaction. But this time the emphasis is entirely on the creation of the design specification documents, specifically, the Standardized BoQ.

The creation of a single, standardized document, under intense activity at various times by several distinct participants, and the need for monitoring, required special attention and led to the development of a very robust module allowing only a single flow of information, avoiding overproduction in the consolidation phase, allowing automatic and immediate error checking, directing to assertive information in the WBS-CW items, and minimizing intermediate files.

PROPOSED UPDATES FOR PRONIC

ProNIC is undergoing an update of its technical contents and IT platform, including integration and interoperability improvements – key concepts of Construction 4.0.

The implementation of new interoperability mechanisms should foresee that BoQ information is available throughout the life cycle of the project, so that existing data structures in a 3D model should be interpretable by ProNIC and associated with WBS-CW items/parameters, and a BoQ created in ProNIC can be a structured data source, usable to support, for example, a Digital Building Logbook (DBL) (Mêda, Calvetti, Hjelseth, et al., 2021; Ribeiro et al., 2022).

In future ProNIC, when the design is BIM-based, the intent is to reduce the design team's work within ProNIC to validations and reviews of the information interpreted by the system. As presented in Figure 5, the system will obtain information directly from the model, filling out some of the parameters and item quantities, and suggesting narrowed down lists of other items and parameters for review by the designers. Remaining and additional items or parameters, which may not exist in the modeled elements, need to be defined by the designers as well.

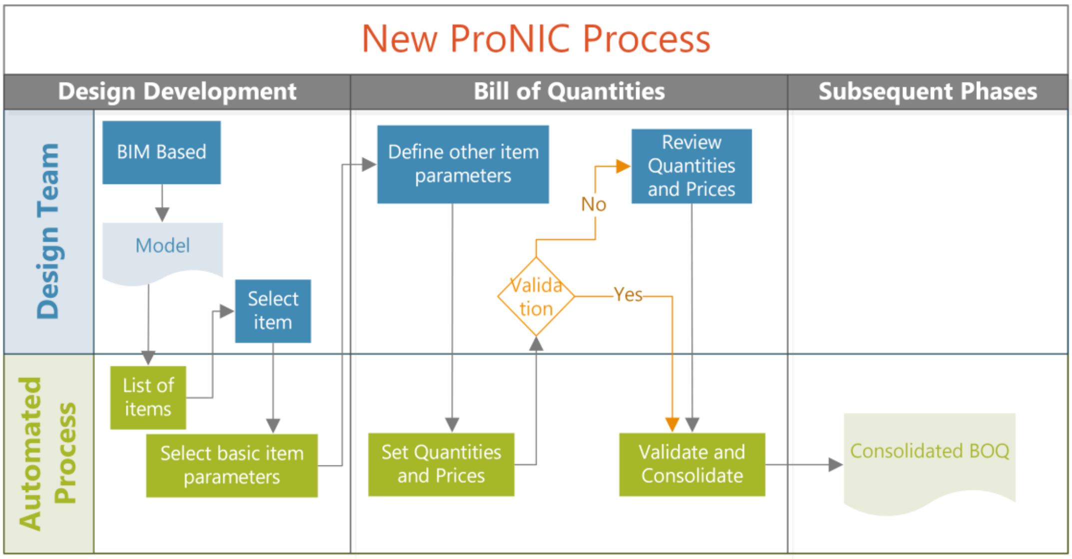

Figure 5: New ProNIC process

Another ProNIC process that can be improved by adopting Lean is the usage of its technical content management module, where the WBS-CW items and technical specifications of construction works are created and maintained by specialist content administrators, for later use by designers. This module allows recent changes in construction technologies and standards to be reflected throughout ProNIC.

To prevent the Underutilization of people, ProNIC should add new mechanisms to simplify repetitive operational tasks such as the updating of references to standards: when standards are replaced with newer versions, the specialist should focus on whether ProNIC's content is still conformant, and not on manually editing potentially hundreds of text fragments. The automated replacement of references to standards also embodies the Lean principle of continuous improvement/pursue perfection and minimizes defects by preventing outdated references.

Lastly, a suggested system-wide improvement is the adoption of a Kanban-like (Arbulu et al., 2007) interface for management of tasks by each ProNIC user, according to their role, and an associated push notification messaging system. In combination with the CDE, this ought to minimize the Wait, Inventory and Motion wastes, by providing streamlined workflows with just the right amount of information at just the right time, ready to be actioned upon.

CONCLUSIONS

The analysis performed in this paper showed that a Construction Information System can ensure a better flow of information, approaching Lean Information Management, by balancing information production, reducing the workload in the construction document production phase, minimizing defects, and eliminating information waste in the design phase. ProNIC brought tangible improvements to traditional workflows by implementing these Lean concepts, despite not being originally conceived under a Lean perspective. ProNIC's key LIM features are:

- Increased reliability throughout the construction process due to standardization of information, error checking, process monitoring, and information available always in its latest version in the CDE.
- Reduction of work overloads due to process automation.
- Each specialized team can focus on activities that add value.

Processes in ProNIC can be further improved by communicating directly with BIM models, reducing complex, error prone activities to mostly verifications and validations. Leveraging Lean principles, proposals for updates related to other operational tasks were also made.

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LEVERAGING BIM AND MIXED REALITY TO ACTUALIZE LEAN CONSTRUCTION

Alessandro Carbonari[1], Massimiliano Pirani[2], and Alberto Giretti[3]

ABSTRACT

Lean construction is made of principles, measures and methods that aim at maximizing process efficiency. Several tools have been developed to minimize waste, maximize customer value, improve the conduction of processes, and pursue other sub-objectives in construction. This effort is becoming more and more important due to the rising construction project size and variety, displacement of resources in diverse geographic locations, high-performance pressure.

This paper reports the development and on-site tests in a real-life demonstrator of two management tools, which apply some principles of lean construction management at the design and delivery phases. The first one takes advantage of the integration between BIM and mixed reality, having the final aim of improving collaboration and communication among the actors involved. The second one exploits BIM modelling and search algorithms within a process-based management platform, in order to facilitate short-cycle planning and distributed decision-making in the production process.

Both tools have been tested in the case of a building renovation project. The results show that they can improve communication efficiency, reduce rework, speed up work monitoring, control and supervising in construction management, and that they can address several of Liker's lean principles, as classified by the 4P model.

KEYWORDS

Lean construction, collaboration, BIM, mixed reality, process.

INTRODUCTION

Many actors participate in the administrative and operational levels of the building business, which makes it a complex business area. The construction supply chain often involves a number of participants even in small construction projects. As a consequence, complexity mainly arises at the interfaces between sub-processes (Dirnberger, 2008; Kolberg et al., 2017) and it has become a critical topic in the field of construction project management (He et al., 2015; Brady et al., 2018). Although there is no consensus on the exact definition of complexity (Ma et al., 2020; Gu et al., 2022), construction processes can be considered to be some of the most complex ventures across all industries, even because the construction industry has experienced speedy progress in projects of rising size and variety. Large scales, sophisticated technical processes, long lead times, huge numbers of people involved, diverse geographic locations, and high-performance pressures make these projects even more complex (Mirza et al., 2017; Zegarra et al., 2019). The developers of the Management 3.0 approach provided several basic

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recommendations (Appelo, 2011): to address complexity with complexity; to use a diversity of models; to assume dependence on context; to anticipate, adapt and explore; to develop models in collaboration; to manage changes. Nowadays, dealing with complexity has never been more important and it requires that an organization is connected with its environment and can adequately react to its changes (Frahm & Roll, 2022).

In such a scenario, most of the principles, measures and methods of planning, designing and controlling applied by lean construction thinking can help the construction industry to deal with external factors that characterize the economic framework, such as high demand (and increasingly scarce resources), low price levels, an increasing competition and constraints determined by political and normative factors. Furthermore, the demand for renewable energies, resource conservation, and rising qualitative standards asks for the adoption of new methods that are able to improve the overall process efficiency, which is one of the main objectives of lean construction (Fiedler, 2018; Neve et al., 2021). Lean construction pursues important goals such as maximizing customer value, continuous improvement of processes, elimination of waste, application of flow and pull principles (Seed, 2015). Waste can be found in many interfaces between processes, due to insufficient communication and collaborative work between teams (e.g. lack of operational management, deployed international teams), but waste can also be generated by low price levels in budgeting and legal proceedings against projects. During on-site activities and in case of a tight work schedule (e.g. parallelization of activities), issues can arise because of mutual obstructions of trades, high costs of rectifying defects, increased need for control by site managers. As a result, projects often are not able to adhere to deadlines (Frahm & Roll, 2022).

In this paper, lessons learned from a three-year EU-funded project entitled “ENCORE – ENergy aware BIM Cloud Platform in a COst-effective Building REnovation Context” will be presented. More specifically, a couple of web services that can help achieve a possible implementation of lean construction methods will be showcased. The first one integrates Mixed Reality (MR) tools to show how they can be used within construction projects to enable collaboration between the design team and on-site users to identify errors/omissions quickly and correctly (Surendhra Babu & Nayath Babu, 2018). This approach makes the decision-making process at the design phase reliable and efficient, because it avoids time delays due to re-works, thanks to an on-site acquisition of information about the designed model and the opportunity to do adjustments in an immersive hybrid environment (Orihuela et al., 2019). The second one is a process-oriented planning and control platform, which exploits BIM, advanced computation and visualization to enhance decision-making in work planning, workspace management, coordination and collaboration during work execution, in order to eliminate wastes due to delayed response to the unexpected, blocked space and passages (Singh & Delhi, 2018). Both tools have been enabled by the development of the design model within a Building Information Modelling (BIM) environment. Experimental tests were performed in the specific case of energy renovation of residential buildings.

The technical details of the platforms will be described in the next chapter. Findings from these experimental tests and lessons learned will be reported and discussed right after that. A conclusions section will end the paper.

TECHNICAL DEVELOPMENT

The architecture of the ENCORE platform (CORDIS, 2023) is structured into four layers: (i) data sources; (ii) data capture; (iii) engines; (iv) applications. It is based on micro-services. The “Applications” layer contains that set of services visible to the main end-users. Among them, the MR web service supports the architect in the creation of renovation options for building efficiency improvement, until one of them is selected as the preferred one. The other web service performs process-oriented management of construction works: it accepts the IFC model of the selected renovation option as input and produces the first work plan and a list of spatial clashes between trades as output. Indeed, site managers and planners can use this platform to check whether the site layout has been arranged accurately, to control the actual work progress, and to update the work plan.

COLLABORATION PLATFORM AT THE DESIGN PHASE

The final purpose of the MR web service was to facilitate the assessment of alternative options for the energy renovation of buildings. In this phase, quite close cooperation between the architect and a few technical experts may be required. Indeed, the feasibility and constructability of renovation options must be checked by means of on-site surveys, due to the limitations and technical constraints caused by the layout and components of the existing building. Thanks to the integration between MR and BIM modelling, the on-site verification can be performed more efficiently, mainly because of the immersive visualization of renovation option models and because of the enhanced collaboration and communication between the architect and involved experts.

The workflow enabled by this platform is sketched in Figure 1. First, the architect is supposed to develop alternative renovation options in the form of BIM models. Every option must be assessed in terms of energy performance. Then, the architect is expected to single out that subset of studies that must be verified by means of an on-site survey, due to constructability issues. Once an expert gets on-site to perform such an assessment, they will enrich every candidate option with information regarding their expert opinion. Eventually, the architect is able to combine all the available information (e.g. feedback received from experts, information embedded in the IFC model) until they can make a decision and select the preferred solution that will be built.

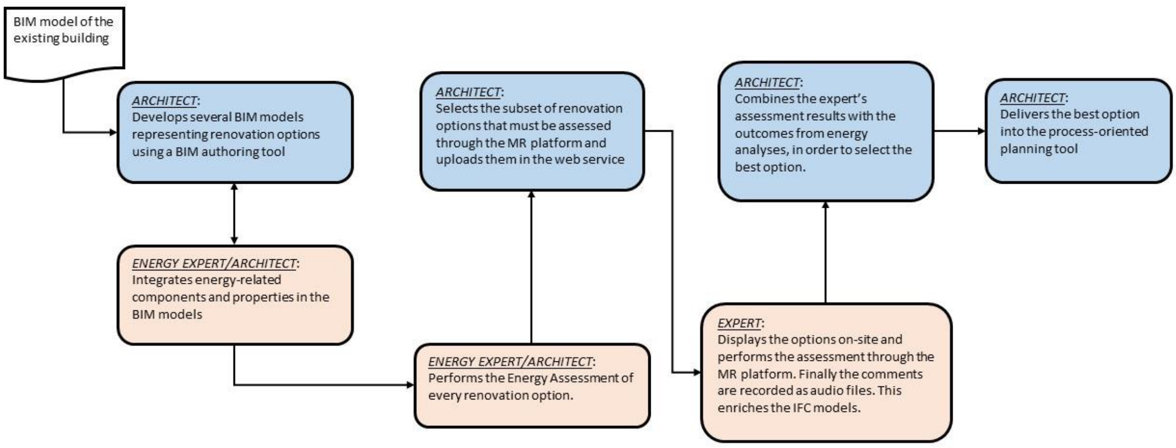

Figure 1: Workflow enabled by the collaboration platform

The platform enables seamless communication and coordination according to the cognitive interpretation of holonic management systems (HMS), which is depicted in Figure 2, and which provides greater agility and increased robustness against disturbances as compared to centralized systems (Mella, 2009). In this view, holons are defined as cognitive units of holarchies that are made of one or more agents and can dynamically reconfigure themselves into new holarchies. As long as this approach is transferred to the case at hand, the holon representing the on-site expert can either make individual decisions or can participate in the collective decision. In the latter case, they give birth to the multi-agent system in a distributed collaborative framework, made up of the on-site expert and members of the design team, thanks to the MR interface and the web service (Figure 2). This avoids requiring centralized decisions only (Valckenaers and Van Brussel, 2016; Derigent et al., 2020).

To this purpose, renovation options are stored in the Encore platform by designers as IFC files and by means of a dedicated Graphical User Interface or GUI (Carbonari et al., 2022). They can be received by the platform through a Restful API. Then, they are passed through an IFC2GLTF translator that converts them into the GLTF 2.0 specification. In this step, a JSON file that contains data and relationships other than geometrical and metadata is created, too. This set of information will be used to produce the game scene by the expert's MR App. In fact, as soon as an expert gets on-site, they will execute the MR app that was developed in Unity 3D 2019 environment with Mixed Reality Toolkit, compiled and deployed in the Hololens by Visual Studio 2019. Once the App has been started and authentication accomplished, the MR App invokes an URL of the App Restful API returning the list of projects to be assessed. Once one of the projects has been selected, this triggers a GET request to fetch the GLTF file ready to be rendered in the game scene of the MR App, together with complementary information included in the JSON file. The model is ready to be aligned by means of visual tags. First, the expert gazes at a tag placed on-site. Then, the MR app sends the serial number to the web server, which localizes the same element in the IFC model. As soon as at least two tags have been scanned, an internal routine aligns the model around the expert. Here is when the immersive experience starts. The user can navigate the model on-site and upload their remarks and suggestions onto the web service, recording voice comments as audio files linked to relevant components of the IFC model. The architect can access the service and go through annotations produced in the assessment until they reach the final decision.

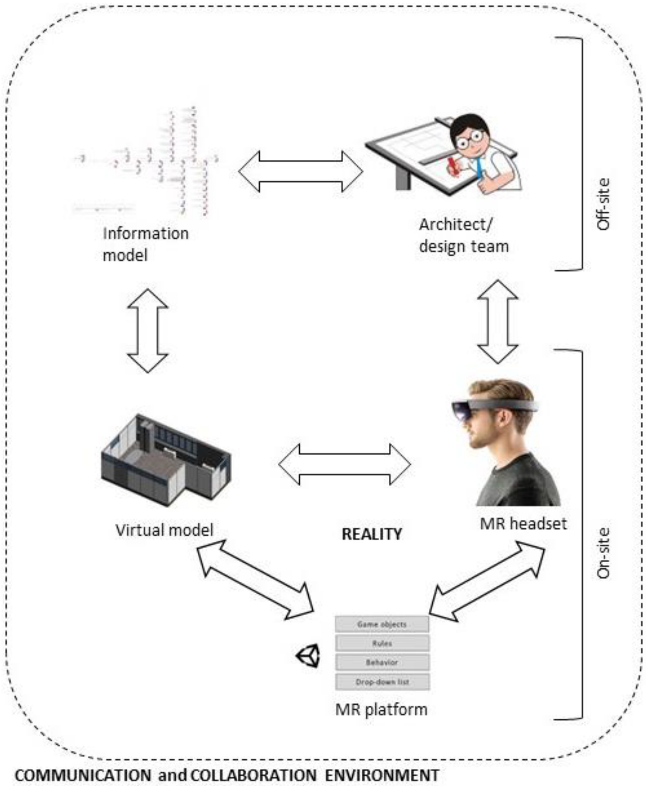

Figure 2: Conceptual diagram of the collaboration platform

PROCESS-ORIENTED PLATFORM TO MANAGE THE EXECUTION OF WORKS

The second web service consists in a proactive, partially automated, human-machine cooperation platform, that was based on the operative interpretation of the Holonic Management System (HMS) architecture, which is made of self-organizing modules (Mella, 2009). Its implementation followed the PROSA (Product-Resource-Order-Staff Architecture) reference architecture (Valckenaers & Van Brussel, 2016), because of its capabilities of mediating between low-level and high-level decisions while sticking to a shared objective.

Basically, this process-oriented platform adopts a process-based representation and an ontology that facilitates the creation of the initial work plan and its regular update during the execution of renovation works (Figure 3). It requires that the renovation project input is provided as a BIM model, including the current state, the demolish phase and the renovation phase. Then, the planner can cluster the components into construction deliverables and can define any applicable milestones (Messi et al., 2021). This web service helps the planner to retrieve information about the BIM product and the applicable price analysis and to bind this information with the construction processes represented in Business Process Modelling Notation (BPMN). As a result, every construction deliverable will be associated with the corresponding process and required resource skills (embedded in the resource/cost analysis source repository valid for the selected price list). Then, a stigmergic planning algorithm works out a plausible work plan labelled as the baseline. This approach facilitates even re-planning during the control phase, once data about work progress are collected from the job site. Finally, an external visualization and spatial simulation tool to check spatial conflicts were developed, in order to warn whether two trades would work in overlapping workspaces.

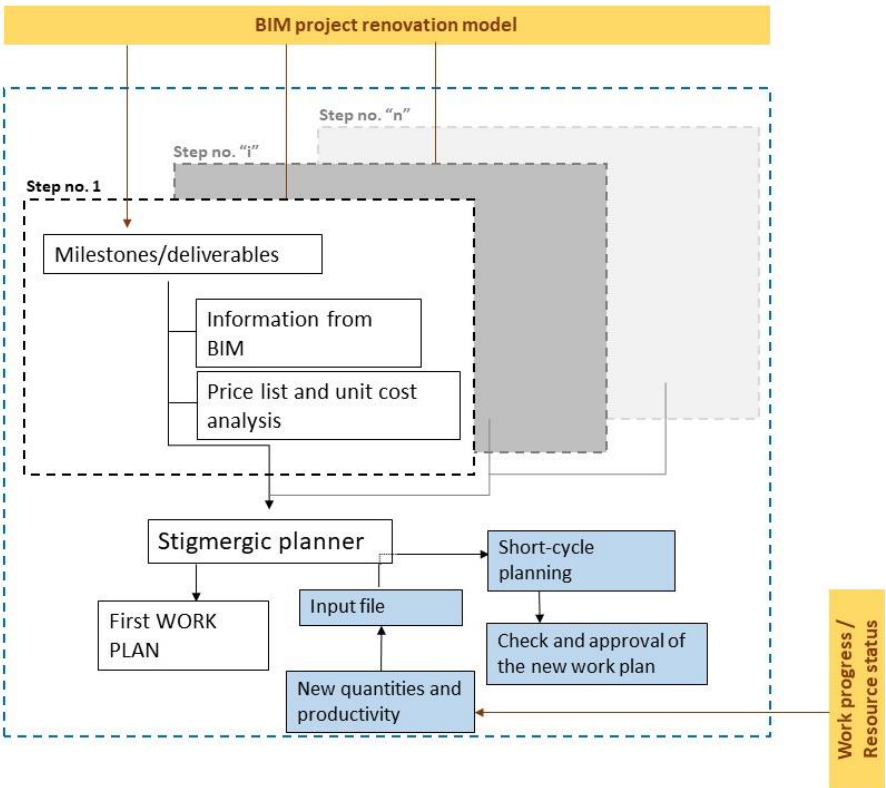

Figure 3: Conceptual diagram of the process-oriented platform

The interaction with the platform is managed through a Web GUI that integrates the sub-services (Figure 4). Once the login is successful, a member of the design team can import two IFC2x3 Coordination View files, which is one of the MVD types provided by BuildingSmart and available as a function in all certified BIM platforms. They are the existing and the to-be-renovated design models of the building, respectively. They can be compared using an in-built function that recalls one of the "IFC Web server" functions to compute differences and work out the list of components to be demolished and the list of components to be built, eventually stored as an editable CSV file.

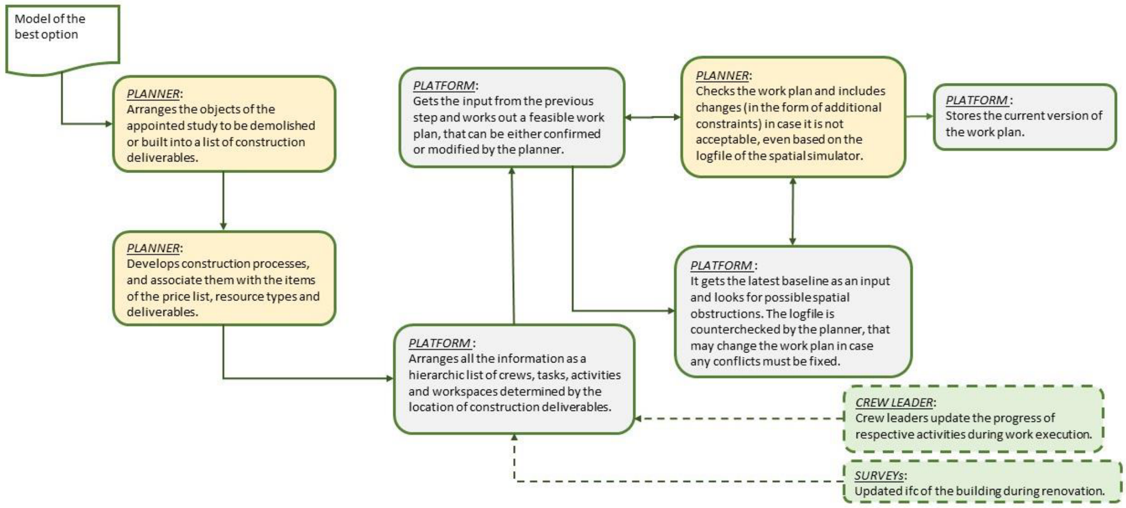

Figure 4: Workflow enabled by the process-oriented platform

The GUI allows the user to edit such a CSV file and generate the list of deliverables. It consists of the rearrangement of those components in order to put together sets of components that will be executed in the same workspace and by the same crew, hence it can be described by one process. A built-in BPMN editor facilitates the creation of BPMN models, either generated from scratch or imported from previous sessions. Thanks to its formal specification in XML, every activity in these processes is linked with the deliverables and the corresponding item of the applicable price list, called by invoking a Python web service. It interacts with the main web service by means of an API REST. Crews are automatically imported from the price list and the analyses of unit costs. Bills of quantities and efforts of crews are generated automatically using the size and other attributes included in the MVDs and deliverable list. They can be counter-checked by the user. All this information is accommodated in a JSON file that is the input of the stigmergic search algorithm, which is started by invoking a Matlab™ simulation environment (Naticchia et al., 2019) and produces work plans. These processes are supported by a multi-model DB developed in ArangoDB (ArangoDB, 2020). The resulting work plan can be imported into an external service developed within Unity3D™, along with the IFC model of the building. Its engine displays workplaces and, then, it checks for spatial conflicts, that is workspaces that may be occupied by different trades at the same time. The list of conflicts can be checked and fixed by the site manager. Finally, a web interface was set up to type in percentage values of work progress. These figures are transferred to the web server by means of a REST API. They overwrite the quantities included in the JSON input file to the stigmergic planner and trigger the algorithm again, until a new workplan is provided as output. As a result, the on-site cooperation among crews providing progress data, the search algorithm for planning, the construction manager, and the information included in the BIM environment realize a collaboration environment, partially automated, that can be regularly and often implemented during work execution.

LESSONS LEARNED

RESULTS OF EXPERIMENTAL TESTS

The tests carried out in the demonstrator building in Caceres showcased the functionalities of the MR service and the main advantages derived from its adoption. The collaboration environment is hosted by a web service in which designers and experts can upload and share design options. As shown in Figure 5-a, several studies or solutions can be associated with a project. They are uploaded by the architect. Once the experts have downloaded those files in their headset on-site, and have accomplished the on-site survey, they are expected to enrich the model with remarks, that are linked with the relevant components of the building and can be retrieved and listened to by the architect at any time. The web page in Figure 5-b shows that as soon as a comment is played, the web service highlights in colour the component to which the comment is attached, thus facilitating the exchange of relevant information.

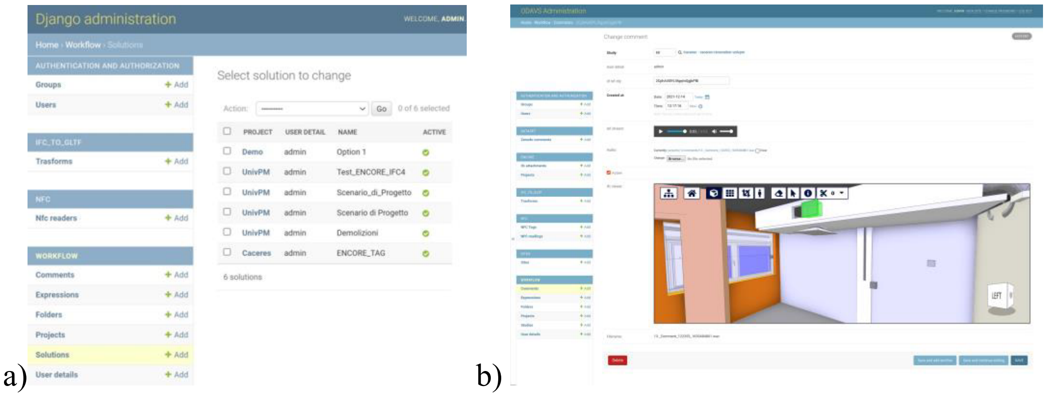

Figure 5: Collaboration environment supporting the evaluation of renovation options

The enrichment deriving from the generation of comments and remarks was made possible by the combined visualization of the physical environment and the virtual model (Figure 6-a). In this Figure the pointer of the user that queries the properties of a vertical pipe is well visible. Figure 6-b depicts an on-site user in the process of interacting with the mixed environment and reaching out a physical component. They can measure the size of a component, can touch and sense the surface of a component to infer the material that it is made of. While interacting with the physical part and wearing the MR headset, the latter does not interfere with these actions. Rather, the MR headset facilitates such navigation and the gathering of additional information. The first-person view of a recording session is shown in Figure 6-c, where the virtual menu handled by the expert is located at the forefront. The recorded remark will be saved in the web service and can be retrieved as shown in Figure 5-b. Additional pictures and videos of these tests are available in a repository authored by Carbonari and Vaccarini (2022).

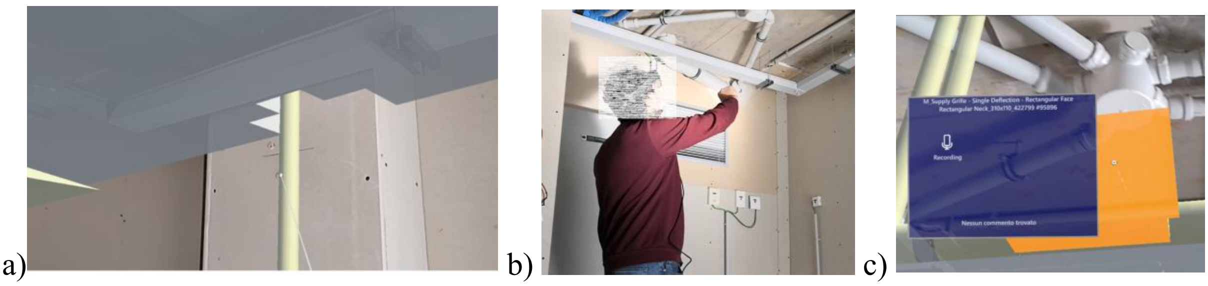

Figure 6: First-person view of an operator mixing information of the current and renovated building (a); use of the platform during the tests (b) and virtual menu to record a comment (c)

Also, the web page of the process-oriented platform that enabled the development of the BPMN processes to manage the renovation works to be executed in the demonstration building located in Caceres is shown in Figure 7-a. According to what reported in the previous section, every node of the process represents a type of activity, which is later instantiated by the system in order to generate the input for the planning algorithm. In other words and as an example, the node “remove plaster” generalizes the two tasks “removal of plaster on the north facade” and “removal of plaster on the south facade”. These instances will be created by the system thanks to the relationships among these nodes, the items of the price list and the deliverables edited and approved by the planner in the previous step. The last step of the planning process that generates the schedule of renovation works is shown in Figure 7-b, along with the baseline worked out by the system. To sum up, the baseline includes five groups of activities: removal of some components and of the plaster; application of insulation layers and of the new plaster on the facades; installation of temporary structures (e.g. scaffolding); installation of sun shading systems and robotic arms to control window opening; replacement of windows. The same data structure and the stigmergic algorithm applied to work out the baseline will be executed during work progress management, in order to perform a short-cycle replanning. The overall duration of this plan spans from March 12th until April 25th, 2022.

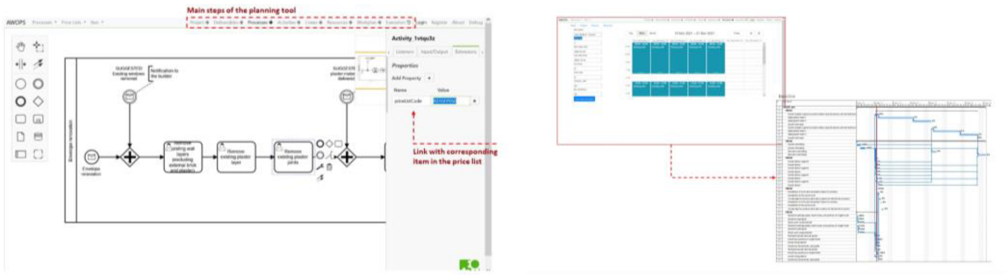

Figure 7: Notation used to model processes (left) and schedule generated by the platform about the renovation works performed in the pilot building (right)

Then, work progress was controlled and plan updates were worked out quite often, as listed in Table 1. At every replanning step listed in this table, work progress was updated and a new work plan was generated by the platform.

Table 1: Re-planning dates during project control

Date	Work progress	Estimate completion date
2022/03/12	Temporary structures are done.	2022/04/25
2022/03/14	Demolitions; envelope insulation (partial).	2022/04/04
2022/03/17	Envelope plaster and insulation; shutters (partial).	2022/03/31
2022/03/21	Shutters; replacement with new windows (partial).	2022/04/04
2022/03/24	Sealing around windows (partial); finish layer (partial).	2022/04/25
2022/03/28	Sealing around windows (partial); finish layer (partial).	2022/03/31
2022/03/31	Renovation works on hold.	2022/04/06
2022/04/07	Installation of shutters (partial).	2022/04/11
2022/04/11	End of renovation works. Construction site dismantled.	-

Work progress was monitored thanks to a web service which could receive percentage values of completion of every single task. The site manager and supervisor may be in charge of gathering such data. The same people can be in charge of changing any relationships among activities and including new constraints whenever applicable, e.g. a supply of windows was late; a precedence between tasks was created due to operational issues. Basically, this is how the platform helps managers to react against disturbances generated by unexpected events occurring during the execution of works. Late deliveries of materials and breaks due to bad weather were the main reasons why the estimated completion date of the project varied so much during the process (see the rightmost column of Table 1). Every time these data had been updated, the planning tool was executed and a new work plan was generated. Then, every work plan was checked using the spatial simulator shown in Figure 8-b. Such a tool displays a coloured box around every workspace; the association between trades and workspaces is listed in the leftmost column in the graphic environment. In case any obstructions were noticed, crew leaders would be asked either to adjust the size of or to move their workspace. In case this action was not determinant, the supervisor or site manager was required to adjust the work plan and fix the issue. In this way, the supervisor was involved in the decision if and only if strictly required.

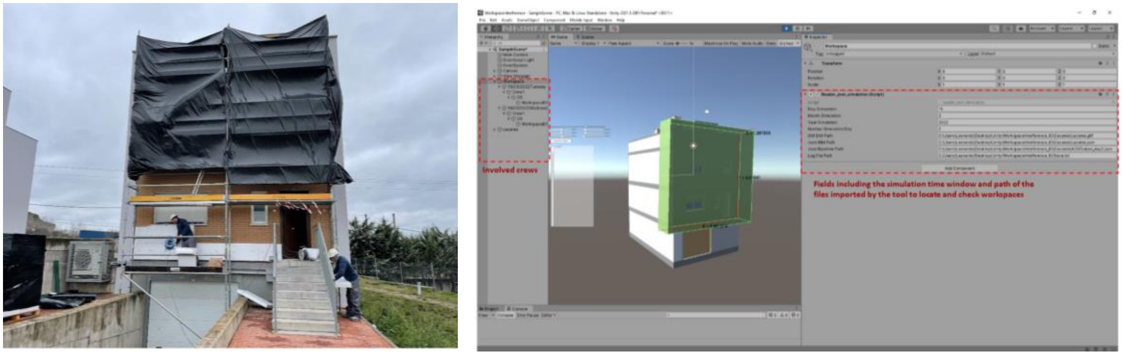

Figure 8: The crews carrying out the execution works on the facades (left) and check of obstructions between trades (right)

DISCUSSION ON LESSONS LEARNED

The volunteers who tested the MR-based platform managed to enrich the BIM model with their opinions, and most of those remarks were available on the platform at the architect's disposal. In particular, 85% of the audio files recorded in the first experimental session and 77% of the audio files recorded in the second experimental session were saved accurately. This is a high percentage if we keep in mind that the volunteers had had no previous experience with the technology. Also, the process-oriented platform supported the creation of the baseline and worked out a new plan on the occasion of each of the eight control milestones of the work progress (Table 1).

Besides these successful quantitative figures, the results of the tests showed that they can address some of the principles underpinning Liker's 4P model (Puram et al., 2021). They are classified into four categories, i.e. philosophy, people and partnership, process, and problem-solving.

The collaboration platform addresses both "process" and "problem-solving" principles. Indeed, it was able to generate a shared environment to be consumed by two types of users in different locations. The first type is the architect and the rest of the design team, which could upload and share information created by experts at any time. The other one is the pool of on-site experts, who could work in an immersive environment and retrieve, edit, or create information enriching the model. These capabilities facilitate the generation of consensus among decision-makers prior to moving forward into the next step and implementing the project. What is more, the information embedded in the virtual model could be combined with the information related to the actual building. The platform allows all of them to organize asynchronously their job. This eliminates waste due to scarce collaboration or difficult communication. In addition, the concurrent assessment of the to-be-renovated design inside the existing building, increased the quality of the assessment and reduced defects in the project. As a result of interviews carried out among the volunteers performing the tests (Carbonari et al., 2022), it came out that the customer/owner could benefit from this platform, because they could have a better understanding of the design and would improve their communication with the design team. Other suggestions concern the extension of the capabilities of the virtual menu in order to increase the possibilities of handling the virtual model, and a more refined selection of the components, so that experts could assess even smaller parts of the project.

The process-oriented platform facilitated the rapid implementation of the execution phase, which is a principle belonging to the "problem-solving category"; it was able to standardize tasks and avoid overproduction, which are classified under the "process" category. In fact, the data model underlying the renovation design models in the IFC files facilitated connection with external sources, such as the price list, and the rearrangement of those data into a format that could be managed by the stigmergic planning tool. Thanks to this approach, the burden of work in charge of the planner got limited and the work plan worked out through computations always minimized the cost function regarding resource usage over time. The second feature is the stigmergic algorithm itself that is able to work out a new plan within a time span in the order of a few seconds. In this case, the combination of BIM and BPMN dramatically speeds up the planning and re-planning process. This figure depends on the number of iterations performed by the search algorithm and by the number of activities. In the case of the demonstrator, which has a limited number of activities, increasing the number of iterations from 10 to 100, would increase simulation times from 3 s up to 29 s. Finally, the integration of the spatial interaction environment as an external tool helped avoid obstructions among trades and helped involve crew leaders at the right time and only when needed, in order to agree on the site layout and the organization required to carry on renovation works.

CONCLUSIONS

Two web services were showcased and evaluated through on-site testing, in order to show how the adoption of a BIM-based work environment coupled with state-of-the-art technologies could realize a lean management approach.

In the first case, mixed reality and BIM models of building renovation projects were combined to create a shared environment inside which many actors could enrich those models with additional information; they could interact with both the physical and the virtual domains; they could cooperate until the selection of the best renovation option was made. The most important benefits brought to the surface by this demonstrator are that communication among the involved actors has been made easier and the quality of the assessment has been enhanced. As a result, the expected collaboration and rework burden will be reduced.

In the case of the process-oriented platform, the combination of modelling techniques to develop process models and the development of BIM project models for the renovation of buildings, allowed the adoption of a planner to speed up the processes for the creation of the baseline. In addition, this technology supported a short-cycle replanning, which realizes a prompt reaction against disturbances generated by external factors and the environment. The BIM and the work plan were imported into a spatial simulator to compute any obstructions between trades that could generate hazards. Several actions in the process were made automatic and did not require manual processing by the planner. Also, decisions could be made at different levels. The adjustment of workplaces to avoid obstructions usually were to be made by crew leaders; however, sometimes a change of relationships between tasks and their start and end dates required a briefing between the supervisor and suppliers. In other words, this approach required the involvement of only the necessary people at every step, with no waste of resource effort. Finally, enhanced visualization of information and models and the continuous availability of data increased operational efficiency.

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BARRIERS TO BIM IMPLEMENTATION IN BRIDGE CONSTRUCTION: A CASE STUDY

Eric Forcael[1], Alonso Castro[2], Francisco Bedwell[3], Euro Casanova[4], Francisco Orozco[5], and Francisco Moreno[6]

ABSTRACT

The purpose of this research was to find the barriers that hinder the implementation of BIM in bridge projects (BrIM). This was done by a bibliographic analysis and the application of an evaluation tool to a case study, corresponding to a Chilean road project with an important number of bridges. Based on the literature, twenty-three barriers were found, which were then validated through the application of the survey to the case study, resulting the main barriers: "Interoperability problems between different BIM software", and "Differences between BIM for buildings and BIM for bridges". Then, a risk analysis was run, concluding that the barriers in bridge projects cause high levels of impact when implementing BIM. Thus, this research may help project and engineering managers to have a first approximation to the most recurring barriers in BrIM and how to rank them according to their impact. Finally, for future research, the findings of this study can be extended to other complex projects —such as bridges— but with different levels of uncertainty, that allow finding new barriers or confirm those found here.

KEYWORDS

BIM, management, bridges, barriers, Chile.

INTRODUCTION

CONTEXT

Since the first industrial revolution, the impact of new technologies has been of utmost importance to obtain better results in the highly competitive areas that have characterized the construction industry. In this way, factors such as resistance to change, and lack of training, financing or knowledge have jeopardized the advancement of new technologies. Building Information Modeling (BIM) has been part of this reality, facing barriers in its implementation. Thus, this methodology has caused a great impact on construction projects, bringing a new way to develop them in each stage (pre-design, operation, maintenance, among others).

This has led to an increase in the number of BIM users, along with government programs for its progressive implementation in different institutions. In this scenario, countries such as

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Chile, through its Ministry of Public Works, have promoted initiatives to increase the use of BIM methodologies in all their infrastructure projects, where the case study considered in this research (a major road project located in southern Chile), is a good example to show this effort.

THE PROBLEM, SCOPE, AND OBJECTIVES OF THE INVESTIGATION

This research consisted of an exhaustive literature search to determine the main barriers to BIM implementation, which were then ratified through the application of an evaluation instrument to various stakeholders belonging to the Ruta Nahuelbuta project, a major road project located in southern Chile. This allowed answering the following questions: what are the most relevant barriers to the implementation of BIM in bridges, what is the probability of these barriers occurring, and what level of severity will these events have in the development of the project?

The general objective of this research was to determine the barriers that limit the implementation of BIM methodology in bridge construction projects, from which the following specific objectives are derived: to determine the barriers to be studied based on an exhaustive literature review; to validate the barriers previously found in the literature, through an evaluative tool; to analyze quantitatively and qualitatively the results obtained.

ACADEMIC BACKGROUND

The necessary information for this research was gathered through a literature review on the fundamentals, vocabulary, and key concepts related to Bridge Information Modeling (BrIM).

BRIDGE INFORMATION MODELING (BRIM)

First, bridge information modeling (BrIM) is essentially BIM applied to bridge projects (Maire & Brinckerhoff, 2012). On the other hand, Cho *et al.* (2009), establish that BrIM corresponds to a 3D concept for design, construction, maintenance, and operation, where the system displays data that allows its use in real-time as conditions change throughout the life cycle of a bridge.

Additionally, Gaitá & Gómez (2014) defined this concept as a set of systems, methods, and digital storage media used to generate the information model of a bridge, which allows combining the information associated with the design and construction from several disciplines.

There are some differences between BIM and BrIM, which according to Bartholomew *et al.* (2015) correspond mainly to a geometric difference since buildings are developed on a rectangular grid system, while bridges are defined with curved or straight horizontal alignments, vertical slopes, elevations, and superelevations. Another difference is the number of specialties since the number of disciplines and trades in buildings is significantly higher than in bridges.

SOME OTHER ASPECTS OF BRIM

Chronologically speaking, Heikkilä (2001) started by determining the content of bridge information models, their technical guidelines and promoting the use of 3D models in Finland. Later, Shirole *et al.* (2009) summarized the main problems and challenges when implementing BrIM in the construction industry. Subsequently, Shim *et al.* (2011) worked on an informative scheme to avoid possible interoperability problems between bridge design and construction processes. Then, Marzouk & Hisham (2012) present a methodology to use BrIM as a tool to estimate costs, who later in 2014 present another cost estimation methodology but adding the estimation of a work schedule for the construction phase (Marzouk & Hisham, 2014). Bartholomew *et al.* (2015) studied alternative BrIM standards and a method for exchanging information modeling data. Meanwhile, Kasireddy & Akinci (2015) analyzed a case study to demonstrate the benefits and challenges of implementing BrIM for bridge life cycle inspection. Other authors, such as Markiz & Jrade (2019) conducted research to demonstrate the feasibility of integrating a support system with the use of BrIM, and overcome subjectivity in decision-making. Finally, Zheng & Xu (2020) conducted risk analyses on the implementation of BrIM.

CASE STUDY

PROJECT DESCRIPTION

The interurban road infrastructure project considered as a case study is called "Improvement of the Nahuelbuta Route", which search for improving connectivity and maximize economic and social benefits of people by reducing transport costs and accidents. This project entailed the improvement and widening of an existing dual carriageway running between two important cities located in southern Chile. It is a public-private partnership (PPP) project, under a modality of Build-Operate-Transfer (BOT), reaching a budget of US$254 million and a road concession period of 35 years (2 years for administrative and project procedures, 3 years for construction and 30 years for operation under a toll mechanism). The project includes an extension of 55 km of dual carriageway, with 17 low-grade intersections, 30 at-grade intersections, 3 toll plazas, 78 bus stops, 2 viewpoints, 2 railroad crossings, 23 pedestrian walkways, 32 km of service roads, 21 km of bicycle lanes, 1 control area, and 15 bridges of different characteristics.

SOFTWARE AND WORKFLOW USED

As for the software used in the project, the architecture and engineering specialties used *Revit* as an information modeling tool for obtaining plans, modeling structures, and calculating the amount of work. *Tekla structures* was used for the modeling of steel reinforcement of bridges.

For the geometric design of road works, *Istram* was used, which is an application specialized in the design of civil engineering projects. On the other hand, it was necessary to use *Autodesk BIM 360* as a cloud platform, to upload, visualize and manage the project models of different specialties and subspecialties. Also, *Naviswork* was used for the compilation and simultaneous review of models, which was able to identify and resolve discrepancies in project coordination.

Finally, *BIMcollab* is a virtual platform for communication and control of the project, through functions such as reporting discrepancies in 3D modeling to the responsible user, sending images of modeling problems, generating reports with the dates on which errors were detected and solved, and thus facilitating review by the client and external users.

METHODOLOGY

BIBLIOGRAPHIC RESEARCH TO DEFINE BARRIERS TO BRIM IMPLEMENTATION

To define the main barriers encountered in the literature when implementing BIM in bridges, an extensive literature review was carried out using the Systematic Literature Review (SLR) method, which is a way of evaluating and interpreting all available research so that it is relevant to a particular research question in a thematic area or phenomenon of interest (Kitchenham, 2004). On this basis, an analysis of the selected documents was then carried out to identify the most frequent barriers and, therefore, the most important according to several authors.

BIBLIOGRAPHIC COMPILATION

At this stage, it was necessary to develop a search protocol, compile a database and make the bibliographic selection, as follows:

Search protocol development

First, the methods proposed by Kitchenham (2004) and Borrego *et al.* (2014) were implemented. In particular, the main filters used were keywords and research questions, among other criteria established in the development of this stage, such as: reading the abstract, title, and internal references of the documents. *Google Scholar* was used as a search engine to retrieve academic content (papers, books, theses, etc.). The keywords used were *barrier*, *building information modeling*, *challenged*, BIM, *bridge information modeling*, BrIM, *construction,* and *risk*.

Database

The search yielded more than 500 bibliographic items, where the vast majority of them came from journals such as *Automation in construction*, *Building and Environment,* and *Journal of Construction Engineering and Management*.

Bibliographic selection

Here, the aforementioned filters were used to select the material, reducing the information to be analyzed to less than 20%. Then, we proceeded to read the content and determine which texts contributed information to the study, obtaining about one hundred documents. Finally, the references of each research were reviewed in search of the most relevant material.

DESIGN AND APPLICATION OF AN EVALUATIVE TOOL

As evaluation tool, a survey was chosen (through the *SurveyMonkey*™) since it is a widely used method and easy to distribute. The survey was applied to stakeholders belonging to the Nahuelbuta Society (owner of the project used here as a case study), and divided into 3 sections:

- Basic information on the respondents (years of experience and specialty).
- Assignment of the probability, between 0 and 100%, of an event, occurring and the level of severity, also between 0 and 100%, it would have on the project. It should be noted that the probability of occurrence was quantified according to the following ranges: very unlikely = 0-20%; unlikely = 21-40%; expected = 41-60%; likely = 61-80%, and very likely = 81-100%. In the case of severity, the ranges were: insignificant = 0-20%; minor = 21-40%; moderate = 41-60%; significant = 61-80%, and disaster = 81-100%.
- Application of a survey to case study stakeholders on the main barriers to the application of BIM in bridge projects.

RESULT ANALYSIS

Based on the results obtained from the surveys, we then proceeded to analyze these results, to construct a ranking of the barriers that impact the most on the implementation of BIM in bridges and a probability-severity matrix associated with this categorization of barriers**.**

BIBLIOMETRIC ANALYSIS

After applying the respective filters, 64 documents were obtained from the literature selection. The purpose of this stage was to distinguish the material according to its origin, year of publication, and the number of cited times. Then, a content analysis was carried out to match the documents that mentioned the same barrier when implementing BIM in a bridge project.

Main sources of information and countries

Out of the 64 documents selected, 46 were journal articles (71.8%); 16 came from conferences (25%) and 2 were theses and 1 survey (3.2%). Most of the research cited comes from five countries. In first place is the United Kingdom with 16%, followed by the United States with 13%; in third place is Hong Kong with 9%, and finally China and Spain, both with 6%.

BARRIERS TO BIM IN BRIDGE PROJECTS

Twenty-three barriers were established, which are listed below and then corroborated through an exhaustive literature review, which results are shown in Table 1. Although the number of barriers to be analyzed may seem to be high, other similar studies have been effective in drawing conclusions from large number of variables (Forcael et al., 2018; Sun et al., 2017):

1) **Need to train a greater number of BIM users:** The number of users trained to work with BIM is limited, and the consequence of this is the difficulty of its implementation.

2) **Ambiguity about the intellectual property of modeling:** Due to the collaborative nature of the BIM methodology, issues related to the intellectual property of the modeling emerge.
3) **Cost associated with the implementation of the software:** BIM works with multiple software, along with the purchase of equipment (hardware) and training courses.
4) **Ambiguity regarding the chain of legal liability:** New obligations for BIM professionals related to work scopes, roles, and responsibilities in case of errors or miscoordinations.
5) **Resistance to change the way a project is built:** Resistance to change due to work culture, lack of commitment and innovation, or the idea that the current way of working is sufficient.
6) **Low use of standards for the description of BIM objects and coding systems:** A BIM standard grants information regarding possible uses, benefits, technical glossary, etc., where the idealistic holy grail of BIM has been to create a common language for builders.
7) **Low demand for the use of BIM by the client/manager:** The lack of demand is due to the lack of knowledge of the program or the client's perception (since his/her requirements are met with conventional tools, he/she considers the implementation of BIM unnecessary).
8) **Interoperability problems between different BIM software:** Fragmentation between participants in each project phase can be caused by the diversity of software and can contribute to the interoperability problems, because of the diversity of software formats.
9) **Lack of knowledge of the benefits of implementing BIM:** The low number of studies of the BIM impact on the projects has caused uncertainty among senior executives and clients.
10) **Time and/or cost for training personnel in the software:** The difficulty of handling the software results in a slow learning pace, bringing a high investment of time and cost.
11) **BIM is still little known and/or complex to use:** BIM is described by users as "rigid" due to the specific order of actions to coordinate the diverse software, along with an "unfriendly" interface, which makes self-learning difficult, made worse due to constant software updates.
12) **Low collaboration among Project participants using BIM:** The "fragmented nature" of the construction field causes the main obstacles of peer-to-peer input.
13) **Lack of government intervention in massive BIM use:** Low participation of the government as a change agent. For BIM to become widespread, the role of the State is essential, through subsidies, courses, or promotion of public projects that require its use.
14) **Low support from managers and decision-makers in the implementation of BIM:** The support offered by top management is a relevant element to implementing BIM in the construction industry, through the necessary investments for training in this methodology.
15) **Lack of experience or expertise in BIM use:** Due to the low number of regulated BIM users, there is a lack of experience, causing difficulties in the implementation.
16) **Limited existence of BIM protocols:** The launch of protocols in the scheduling phase is crucial to ensure consistency in the information and formatting styles for BIM implementation, if not, it increases the occurrence of mishaps.
17) **Changes in workflows within and between projects:** Because of the collaborative nature of BIM, it is important to give way to radical changes in the workflow. These changes are not entirely linear but produce feedback loops between BIM specialties.
18) **Limited access to a stable connection to servers for storing and coordinating information:** There was no stable internet service or hardware (*IT infrastructure*) with the necessary capabilities to be efficiently connected to external or internal servers.
19) **Cybersecurity risk:** Cybersecurity becomes a major threat when an unauthorized user or hacker get access to a BIM project. In addition, confidential information, such as electronic signatures on documents, can be easily forged or replicated, creating authenticity doubts.
20) **Need for a BIM manager in projects:** Because information models are shared among users, it is crucial to hire an employee who updates the BIM data with accuracy.

21) **Low availability of specialized BIM software for bridges:** It is caused due to the low availability of specialized software that has specific "families" for the modeling of bridges.
22) **Difficulty in making updates to bridge models on-site:** When wanting to perform on-site inspections of a bridge to update the information of its real conditions, a lack of flexibility to represent and exchange information parametrically has been found.
23) **Differences between BIM for buildings and BIM for bridges:** The differences that contrast BIM and BrIM lie in the procedure for modeling the parts of each project, since, in general, roadway elements must be adapted to the geometry of the terrain.

Table 1: Barriers found in the literature

Authors \ Barriers	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
(Ahmad et al., 2018)		•				•		•	•	•									•				
(Ahmed & Hosque, 2018)								•			•												
(Ahmed et al., 2014)						•	•		•	•	•	•		•	•			•					
(Ahn et al., 2016)				•				•			•		•				•						
(Al-btoush & Haron, 2017)					•												•						
(Arshad et al., 2019)		•		•		•		•								•			•				
(Azhar et al., 2015)	•	•	•	•		•		•		•		•				•				•			
(Bartholomew et al., 2015)																							•
(Chan et al., 2019)	•	•	•		•	•		•				•		•	•								
(Chiu & Lai, 2020)	•						•			•	•	•	•	•									
(Costin et al., 2018)			•	•	•	•		•															
(Dayan et al., 2022)					•			•					•					•		•		•	
(Forcael et al., 2020)								•				•						•					
(Gaitá & Gómez, 2014)																					•		
(Gerrish et al., 2017)						•					•												
(Kasireddy & Akinci, 2015)																					•	•	
(Kiani et al., 2015)		•			•				•		•												
(Maire & Brinckerhoff, 2012)																					•		
(Marefat et al., 2018)					•		•				•	•			•	•							
(McGuire et al., 2016)				•			•	•													•		
(Mehran, 2016)		•		•				•	•					•	•	•							
(Migilinskas et al., 2013)			•							•		•		•									
(Ng & Lai, 2016)			•				•		•		•	•	•					•					
(Porwal & Hewage, 2013)		•		•																			
(Saieg et al., 2018)	•		•					•															
(Saka & Chan, 2020)					•	•	•		•		•		•	•									
(Seyis, 2019)		•								•		•			•					•			
(Ullah et al., 2019)		•	•		•	•	•	•	•				•	•	•	•							
(Vass & Gustavsson, 2017)													•				•						
(Zhao et al., 2018)	•	•	•		•			•				•			•	•			•				

CASE STUDY EVALUATION OF THE BARRIERS FOUND IN THE LITERATURE

To evaluate the impact of the barriers found in the literature, an evaluation instrument (survey) was applied to a group of 17 professionals belonging to the case study described above. This survey consisted of two parts: questions associated with the probability of occurrence of an event (in this case a barrier), and questions related to the severity that could cause the occurrence of such an event. Based on the results of both indicators (probability and severity), the impact caused by the existence of barriers in the implementation of BIM in bridges was calculated.

For the validation of the evaluation instrument applied, it is necessary to ensure its understanding and whether its design is self-explanatory (Forcael et al., 2022). For the present study, eminent practitioners and researchers reviewed the survey and made relevant comments to improve its comprehensibility, repeating the process until the survey was fully refined.

Once the data was processed, Cronbach's alpha coefficient (α) was calculated to evaluate the reliability of the survey, ensuring the survey's objectivity. This value was calculated with equation 1, where K is the number of questions, V_i is the sum of the variances of each question and V_t is the variance of the total results of the respondents.

$$\alpha = \frac{K}{K-1}\left(\frac{\sum_{i=1}^{K} V_i}{V_T}\right) \quad (1)$$

Along with the validation of the interview described above, according to Oppenheim (2000), a pilot interview was also applied to measure and calibrate the interviewee's response time and ensure that the questions were explicit and did not confuse the interviewee. Thus, for the survey applied, Cronbach's alpha values obtained were 0.869 for questions related to probability and 0.909 for questions associated with severity, values with a more than acceptable reliability according to Doloi (2008). The response rate of the applied instrument reached 47%, which is considered satisfactory as it exceeds the minimum value suggested by Fellows & Liu (2015). The survey is available on request from the authors. The sample consisted of architects, builders, civil engineers, BIM managers, and BIM coordinators, whose profiles are shown in Table 2.

Table 2: Respondent profile.

Labor sector	Private	50%
	Public and Private	50%
Professional Career	Architect	25%
	Civil Engineer	50%
	Builder	13%
	Other	13%
Current area of work	Construction	13%
	BIM Management	25%
	Engineering	63%
Work experience	5 - 10 years	25%
	10 - 20 years	13%
	+20 years	63%
Experience with BIM	0 - 2 years	25%
	2 - 5 years	25%
	5 - 10 years	38%
	+10 years	13%
BIM knowledge level	Self-acquired knowledge	38%
	Training	38%
	Masters in BIM	25%

IMPACT ANALYSIS OF THE BARRIERS PRESENT IN BIM FOR BRIDGE PROJECTS

Calculation of indexes

The methodology proposed by Akogbe *et al.* (2013) was used to calculate the indexes, which allows the factors to be classified in terms of impact, using probability and severity responses:

- Probability index (P.I.): represents the probability of occurrence of an event, with values between 0% and 100%, and calculated with equation 2.

$$I.P = \frac{\sum_{0}^{100} a_i * n_i}{N} \quad (2)$$

Where a_i represents the value assigned to each answer (0%, the impossibility; and 100%, the certainty); n_i represents the frequency of each answer, and N is the total number of answers.

- Severity index (S.I.): represents the severity of an event on the project if it were to occur, ranging from 0% (no severity) to 100% (total severity), calculated with equation 3.

$$I.S = \frac{\sum_{0}^{100} b_i * n_i}{N} \quad (3)$$

Where b_i represents the value assigned to each response (where 0% is no impact and 100% is high impact); n_i represents the frequency of each response and N is the total number of responses.

- Impact Index (I.I.): impact of an event based on the probability of occurrence and its severity, classifying the barriers according to their risk for the project and calculated with equation 4.

$$I.P \; x \; I.S = I.I \tag{4}$$

Impact Index Ranking

Table 3 shows the results from the evaluation tool, which are broken down into the probability index (P.I.), the severity index (S.I.), and based on these two indicators, the impact index (I.I.).

Table 3: Impact factors ranking.

Barrier	P.I.	P.I. Ranking	S.I.	S.I. Ranking	I.I.	I.I. Ranking
8. Interoperability issues between different BIM software.	85%	3	87%	4	74%	1
23. Differences between BIM for buildings and BIM for bridges.	86%	2	80%	6	69%	2
16. Limited existence of BIM protocols.	72%	10	82%	5	59%	3
15. Lack of experience or expertise in BIM use.	76%	7	76%	7	58%	4
17. Changes in workflows within and between projects.	81%	4	64%	13	52%	5
21. Availability of specialized BIM software for bridges.	56%	16	92%	1	52%	6
6. Low use of standards for BIM object description and coding systems.	78%	6	64%	12	50%	7
12. Low collaboration between project participants using BIM.	74%	9	66%	11	49%	8
5. Resistance to change the way a project is built.	78%	5	61%	14	48%	9
19. Cybersecurity risks.	52%	19	90%	2	46%	10
3. Cost associated with software implementation.	76%	8	59%	17	45%	11
22. Difficulty in making updates to bridge models on-site.	46%	21	88%	3	41%	12
1. Need to train a greater number of BIM users.	61%	15	67%	10	41%	13
9. Lack of knowledge of the benefits of implementing BIM.	70%	11	58%	20	41%	14
2. Ambiguity about the intellectual property of modeling.	66%	13	58%	19	38%	15
4. Ambiguity regarding the chain of legal liability.	69%	12	53%	22	37%	16
7. Low demand for the use of BIM by the client/manager.	64%	14	54%	21	35%	17
11. BIM is still little known and/or complex to use.	48%	20	70%	9	33%	18
14. Low support from managers and decision-makers in the implementation of BIM.	55%	17	60%	16	33%	19
10. Time and/or cost for staff training on the software.	52%	18	61%	15	32%	20
18. Limited access to a stable connection to servers for storing and coordinating information.	40%	23	76%	8	30%	21
13. Lack of government intervention in massive BIM use.	41%	22	59%	18	24%	22
20. Need for a BIM manager on projects.	90%	1	25%	23	22%	23

It can be seen that the “Need for a BIM manager on projects” is the barrier with the highest probability of occurrence according to the respondents (90%), followed by “Differences between BIM for buildings and BIM for bridges” (86%), and in third place “Interoperability problems between different BIM software” (85%). In terms of severity, the factor with the highest index was “Availability of specialized BIM software for bridges” (92%), followed by “Cybersecurity risks” (90%) and “Difficulty in making updates to bridge models on-site” (88%).

The impact index (I.I.), as previously explained, is related to the two previous indexes, and provides an overview of the impact of the barriers on the project. The first is "Interoperability problems between different BIM software" (74%), which is not surprising, since it is in the top five of the previously ranked indexes. Next are "Differences between BIM for buildings and BIM for bridges" (69%), "Limited existence of BIM protocols" (59%), "Lack of experience or expertise in the use of BIM" (58%), and "Changes in workflows within and between projects" (52%). In this research, any barrier that exceeded the median I.I. was classified as relevant. Thus, the P.I. and S.I. of the barriers mentioned in the classification by I.I. have values that meet this criterion, except for "Changes in workflows within and between projects".

Probability-severity matrix

Figure 1 shows a probability-severity matrix, which was used to determine the impact zone in which each barrier is located. The impact categories range from very low (lower left zone), to very high (upper right zone). The matrix design is based on the research of Dumbravă & Vladut-Severian (2013). It is seen that most of the factors are in the very high and high impact zone.

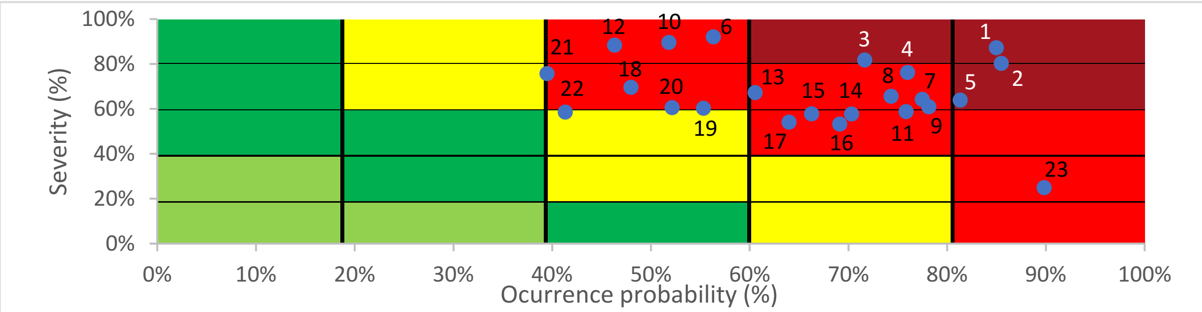

Figure 1: Probability v/s severity matrix

CONCLUSIONS

In terms of contributions for practice, this research may help project and engineering managers to have a first approximation to the most recurring barriers in BrIM and how to rank them according to their impact. Despite the findings of this study are based on survey responses from BrIM projects, they can be extended to complex projects with different levels of uncertainty. As found, this research shows that "Interoperability issues between different BIM software", "Differences between BIM for buildings and BIM for bridges", "Limited existence of BIM protocols", "Lack of experience or expertise in the use of BIM", and "Changes in workflows within and between projects" are the main barriers to implement BIM in bridges. Therefore, a project manager should pay attention to the existence of BIM protocols for bridges and to count on professionals with proved BIM experience. From a technical point of view, it is relevant to focus on interoperability between BIM software packages and the main differences found when using BIM for bridges instead of BIM for buildings. Finally, the last barrier found —related to changes in workflows within and between projects—, accounts for the importance of having competent managers to coordinate the whole project properly.

The only factor unique to bridge projects was the "Differences between BIM for buildings and BIM for bridges". It is also important to mention the close relationship between the barriers "Interoperability problems between different BIM software" and "Limited existence of BIM protocols", as they may allow writing a guide for interoperability between software to be used. Finally, in terms of risk, as most of the barriers were grouped in the upper right corner of the probability-severity graph, i.e., high probability of occurrence and high severity levels, it was possible to confirm that the barriers present in bridge projects generate high levels of impact when implementing BIM. Because of the exploratory nature of this study, for future research it is recommended to consider a larger number of interviewed professionals belonging to multiple bridge projects, which could provide other barriers or confirm those found in this study.

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THE ROLE OF LEAN IN DIGITAL PROJECT DELIVERY

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ABSTRACT

The role of digitalization in delivering construction projects is ever increasing as digital tools and processes are pervading the entire construction lifecycle. Lean processes have a proven track record in improving construction project delivery while playing a positive and important role in the deployment of digital processes.

This paper discusses the key lean drivers for introducing digital production management systems to support efficient production planning, monitoring and controls. The paper also highlights the role of Last Planner System® (LPS) in the development of centralized digital command rooms to integrate disperse project teams. The research methodology was action research using a case study of a data centre.

The use of digital tools to support the last planner system can affect the behaviours of the participants. Improved transparency with an increased understanding from using digital platforms can improve the understanding between project stakeholders. It was found that the lean collaborative processes based on the LPS, especially the lookahead and commitment planning processes contributed significantly to the successful deployment of the digital platform and improvement of the control cycle.

To manage global networks and integrate fragmented project teams, Lean construction methodology supported using digital tools can enhance the collaborative environment. Digital construction can enhance the knowledge sharing that in turn improves social networks that can increase innovation.

KEYWORDS

Lean Construction, Digitization, Project Management, Last Planner System®

INTRODUCTION

Lean thinking and lean processes have proven to be successful and to positively influence major operations and improve productivity. Using digital tools to support lean concepts by providing near real time information that can be formatted and displayed can support multi stakeholder engagement and increase the effectiveness of collaborations (Sepasgozar et al. 2021). This information should underpin lean social collaborative production planning, where information is used to understand productivity rather than direct operational decisions using data alone (McHugh, et al., 2021). The correct management of digital platforms can support and increase the effectiveness of lean construction methods for project teams. The use of cloud based platforms and organized data, project teams can share a single source of truth that can improve communication to avoid delays and minimize reworks (Quiso et al. 2020).

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LITERATURE REVIEW

The international construction industry is vast, according to the Confederation of International Contractors' Association (2022), global construction industry represents a global turnover of US$14 trillion and employs around 120m people. The industry relies on specialized contractors and designers who work with international clients. Standardized delivery methods for projects are desired to manage productivity. Productivity loss is experienced when a contractor has not accomplished anticipated achievable or planned rate of production (Gibson and Edwards 2015). Lean Construction (LC) methods have been identified as a possible improvement to construction project management. Technology has been identified as key element to support LC, however barriers to implementation include technical barriers, organizational fragmentation, and organizations unwilling or prepared to make the necessary changes to adopt LC (Hamzeh et al., 2021).

The availability of skilled workers is an issue for the industry with the current global growth (Ceric & Ivic, 2020). This deficit of skilled operatives effects the quality and overall project performance resulting in higher costs (Karimi et al., 2018). Utilizing key staff and bringing the required expertise is a challenge to the construction industry. The availability of skilled staff and underutilization of staff hinders construction productivity.

There is an increased focus on the adaption of construction 4.0 technologies and methodologies (Bolpagni et al., 2022). The digitalization of the construction industry and the advancement of Building Information Modelling (BIM) have highlighted opportunities for projects to harness construction 4.0 technologies (Kunz & Fischer, 2020; Sacks et al., 2010). The Internet of Things (IoT) can seamlessly interconnect components and improve the quality of performance and output of information systems. While Industry 4.0 is the bedrock of technological change through an adaptable tool to ensure desirable change and automation occur in the process of adopting IoT and Lean concepts, which was supported in (Ballard & Howell, 2003; Dave et al., 2013, Dave et al., 2016). Digitalization can potentially prove beneficial for large scale projects where project teams are fragmented and where project scope is vast. Effective and immediate access to information minimizes the time and labour needed for retrieving information and reduces the occurrence of ineffective decisions that are made in the absence of information (Ergen et al. 2007).

The adaption of digital technology and platforms can assist lean construction where production networks can be deployed for all stakeholders that can improve productivity both on and off site. This can improve efficiency, accountability, sustainability and scalability where dispersed project teams can collaborate (Frazzon et al. 2013). These processes can further be supported by providing digital collaboration spaces where teams can join collaborative meetings in digital operation rooms. This improves the effectiveness of collaborations as the correct stakeholders and decision makers are available to participate in the sessions. With live digital information at hand stakeholders are prepared for collaborative meetings where the project information available on the cloud for interrogation which increases the value of the meeting (McHugh, 2021).

LEAN BASED MANAGEMENT

Lean thinking, tools and methodology can influence major operations and improve productivity. Continuous innovation and supporting a learning environment are core elements of lean construction (Zhang and Chen 2016). As construction projects become more complex, specialization of specific functions has introduced complex project organizational structures and interfaces that require integration to complete the project. How a project performs is linked to how efficient the bounded activities are planned, managed, and how permeable the boundaries are to support information flow, share knowledge and learnings (Hobday, 1998).

The use of digital tools supporting lean concepts of management can provide innovative solutions to maximize the availability of near real time information. This information should underpin lean social collaborative production planning, where information is used to understand productivity rather than direct operational decisions using data alone (McHugh, et al., 2021). Construction research theories provide insights, but it is the nature of the markets—notably, the diverse objectives of stakeholders and the procedures and their practices in pursuit of self-oriented benefits—which are the main impediments to achieving greater coordination and collaboration (Fellows & Liu, 2012).

Digital platforms can support the generation and sharing of knowledge and will need to be adapted and improved as construction management progresses. Hamzeh et al., 2021 introduced the concept of Lean Construction 4.0 which recognizes the advancement of digitization in the industry with the need for a human centric rather than a technologically centric philosophy to advance the industry. Using cloud platforms and organized data, project teams can develop an information system where all stakeholders can commit and also be held accountable (Hicks 2007). This also provides a collective collaborative platform where the project interests are highlighted rather than interest of just individual stakeholders. This reinforces positive behaviors where project constraints can be identified and shared clearly, and project commits can be shared and validated using acquired data.

RESEARCH METHOD

Action Research (AR) has expanded over the years across varied disciplines as a means for improving the quality of interactions and understanding among people in social situations (Burns, 2005). In this study some of the authors were participant in the study. The results and actions outlined were created collaboratively with the project participants. The study focuses on generation of public sphere where participants can engage. This participation is relevant in critical participatory action research. However, authors have emphasized that the key form of participation in this kind of research is participation in a public sphere and participation with others in communicative action. This approach is analogous to a conversation in which people strive for intersubjective agreement about the ideas and the language they use, mutual understanding of one an - other's perspectives, and unforced consensus about what to do (Kemmis et al., 2013).

A case study was developed to represent the research where a "case study" can be defined an intensive study about a person, a group of people or a unit, which is aimed to generalize over several units (Heale & Twycross, 2018). Case studies by their nature, are more concerned with depth of analysis than with generalization (Borgman, 2015). This study follows on from previous research developing digital social environments (McHugh et al., 2019; McHugh, et al., 2021). Case studies provide a deeper understanding, for example, causal relationships than controlled experiments do (Host et al., 2012).

The research will be led by one of the authors who is an industry practitioner of lean construction. Action research is participant research that comprises of taking actions while studying a problem whilst also producing knowledge accumulating experience and contributing to the discussion of problems (Collatto et al. 2018). This research will support the development of an information system to support the efficient phased handover process that is essential for commissioning stage of the project.

CASE STUDY

The case study is on a €1.2bn data centre project where lean project management systems have been used during the construction phase. The project was based in Ireland and had initially started in 2016. This facility is an 86,000 m² structure consisting of 8 single storey data halls with associated electrical rooms and external backup generator systems. The facility also consisted of an administration block and external security centre. This study was carried out on the third phase of construction on the campus. For this phase there was a fundamental change of the design where a First of a Kind (FoK) cooling system was designed for the client. This required significant equipment changes along with layout and build sequence alterations.

This study will focus on the final phase of construction the Commissioning (Cx) phase. The (Cx) phase of data centre projects have traditionally proven to be more difficult to execute as there are more stakeholders involved. Since they are highly dependent on each other, developing schedules in parallel without adequate coordination can lead to misconceptions and, therefore, a great deal of rework (Garcia et al., 2004). It has been identified that the Cx phase requires a greater level of collaboration with an increased integration of project stakeholders. The problem posed was how to gather, share and use information acquired to integrate construction, commissioning, and quality functions for all stakeholders.

Digitized LPS was use on previous project phases on the site where they were completed and handed over to the client defect free. The resultant predictable and reliable phase handovers enabled the client to challenge the team to construct and commission a FoK construction project. This case study documents how digitization supported the process and assisted the integration of teams and it supported the execution of complex tasks.

PREPARATION FOR DIGITAL COLLABORATION

The Production manager, Cx manager and programme manager developed a high-level work breakdown structure. Early engagement from the project vendors and design team highlighted project constraints. The Cx phase of the project started with a pull planning session where all stakeholders developed a commissioning plan. There were approximately 20 different organizations ranging from designers, specialist vendors, quality assurance and trade contractor teams. This exercise identified and exposed issues with the construction and Cx sequencing and provided the team with a greater understanding to complete the Cx programme. Figure 1 illustrates the progression from reviewing the proposed master schedule to development of an actionable commissioning programme,

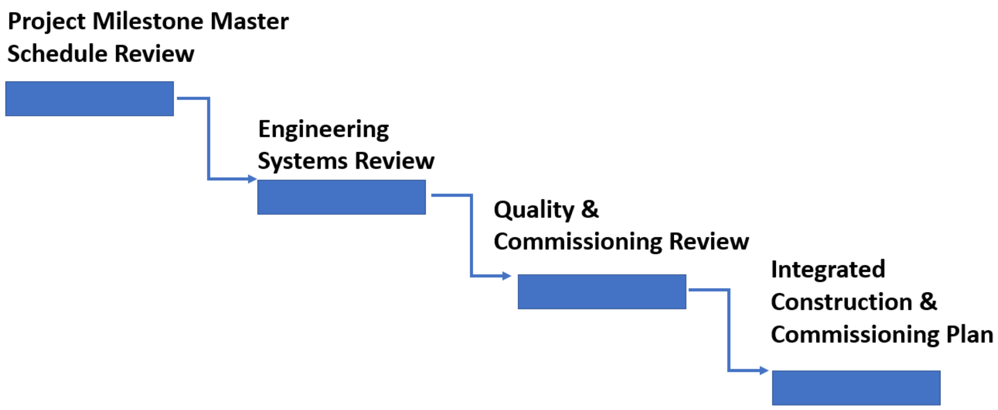

Figure 1: Cx Framework development phase

This was then cascaded to the trade contractors to review and resource in advance of a pull planning digital mapping day. A digital hybrid method of mapping was used for the first time instead of using ‘post-it’ notes in the room. Project resequencing and constraints were highlighted in the collaborative session. A dedicated digital hub (Figure 2) was used with technology to virtually interact using web cameras, mist microphone room pick up and high-definition touch screens and sound bars. This room was designed to improve interactions between site-based teams and virtual remote teams. The use of touch screens and smart microphone functions improved collaboration between team members.

The use of this technology allowed interaction between professionals connected remotely and the ones in presence. The command room has been present on the project since the first phase. The digitization of the room began early in the project and has evolved and improved on each phase where new available and affordable technology has been introduced. The room was designed with collaboration in mind where interaction is key to good communication and collaboration.

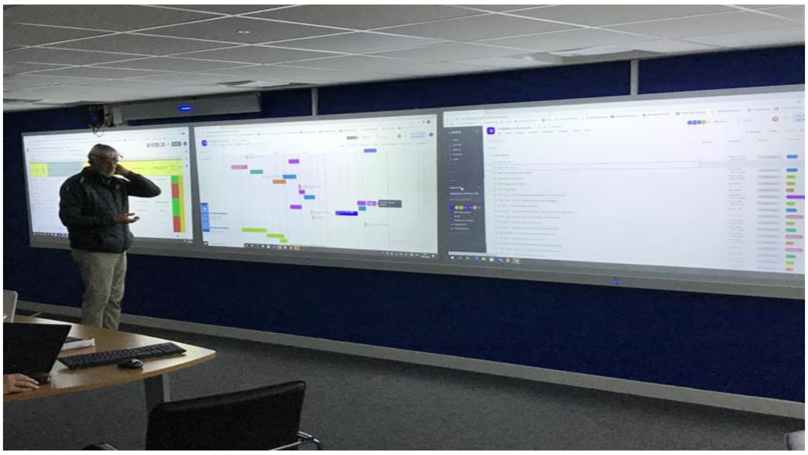

Figure 2: Digital hub with Digital Pull Planning sequence

DAILY OPERATIONS PREPARATION

The quality of collaborative meetings observed relied on participants being informed and prepared. Information quality is key to the success, shared information platforms aided the acquisition and validation of key project information. The identification and tracking of key activities were important to successfully achieving defined targets. Therefore, the more extensive and balanced the inputs of information (i.e., options, alternatives, predictions, and criteria, which we call collectively decision contents), the more informed the decision basis becomes (Kam and Fischer 2004). Following the initial mapping day there was a series of targeted workshops to map the critical air, water & electrical systems. Visilean (Dave, B., 2013) was used to prepare these plans and it was used to highlight and manage constraints raised.

Figure 3: Weekly Work Plan PPC live dashboard

This plan was then further broken down to develop look ahead planning and weekly work plans using the Last planner System ® (LPS). Digital platforms were identified to gather information and share the status of the project as shown in (Figure 3). BIM 360 Field was used to prepare and manage the quality check sheets which are necessary for the Cx stage. There are limited mitigation measures at Cx phase for not completing the preceding Cx activities, therefore it is necessary to have an accurate picture of the current activity status. This allowed project teams to develop and manage the required check sheets collaboratively. This provides the Conditions of Satisfaction (CoS) necessary for seamless staged handovers. Daily morning huddles previously held on site were relocated to the digital command room. Digital white- boards were prepared by each trade contractor and vender. This board was designed to include client issues, design issues, quality issues and commissioning status of activities.

A Cx dashboard was developed to capture the project status and improve communication between project stakeholders. Constraints were raised and incorporated into daily meetings where the team removed constraints and improved the delivery process. The status of each piece of equipment was managed for installation. The status of each piece of equipment tracking was essential to map the critical Integrated system test (IST). IST can begin when all equipment has passed the required testing and initial commissioning.

Daily huddle meetings are an important meeting in the production control system cycle. This is where daily commitments are reinforced and where the team members collaborate to execute defined assignments, this is where the quality of the planning and preparation is validated. It is important that commitments can be communicated effectively and trade to trade handovers are delivered efficiently. These meetings are the foundation for all future planning and ensure that the quality of the installations is validated and ready for the next stage of commissioning. Dashboards were an effective way of managing commitments as shown in figure 4.

Figure 4: Cx Dashboard

Reporting & Communication

Project data was collected using multiple digital platforms. This information was integrated by developing Business Intelligence (BI) dashboards. Dashboards played an important role for communication between project stakeholders. PowerBi® platforms were used to gather information from different sources to integrate into a single visualisation platform. Data was collected from multiple platforms that were used for daily works planning, material delivery, safety documents, quality documents, design, with laser and scanning/reality capture sources. This data was formatted and sorted by area and by utility and then by trade contractor.

It was important to code and identify all assets and functional areas correctly to allow data from different formats to be integrated correctly. There were over twenty different organizations imputing information daily into the system from daily activity reporting to quality check status and BIM coordination and scanning. This form of bottom-up communication really meant that there were over one hundred individuals managing the Cx programme between site teams and planning teams. It was important that all teams could work effectively and the ability to report accurately on daily Cx activities was important. This allowed teams to work effectively together with a shared understanding of the project.

The purpose of developing of digital dashboards was that they could be used in a digital control room to support allowed project teams' ability to communicate effectively. The dashboards were configured to be used at the different stages of the LPS. Short term forecasting and PPC dashboards were primarily used for site supervision collaborative meetings. Weekly work plan dashboards were used at daily huddle meetings. The information collected from the field fed directly into operational and planning dashboards.

Figure 5: Quality Dashboard

The project team focused on improving the sequencing and trade to trade handovers of this FoK project. Quality trade to trade handovers are an important gateway for the Cx stage of the project. The status of equipment was visually displayed on the quality dashboard (Figure 5). There are multiple stakeholders involved in this quality function. Defining what the correct parameters and requirements for each stage is important. Communicating this and measuring adherence to the defined parameters is also required. Firstly, in design the quality of the documentation and design modelling is a make ready need for construction. Procurement of materials and the validation of installation by construction teams is then required. The demonstration of how to present the soundness of installations to the project quality teams is required. The development of a detailed quality plan ensured that all stakeholders understood the steps to handover installed works. The sign off for the equipment and associated services before the Integrated Service Test (IST) is the focus of the Cx phase of the programme. In terms of planning, each sequence of work is directly linked to the next.

Forecasting and ensuring quality inspections passed first time was a key focus for delivery. Scheduling quality walks and confirming commitments were ready is an important process for accurate look ahead planning. This ensured that all project stakeholders could schedule and utilize their resources effectively (Figure 6). The raising of issues was promoted to provide learnings and to support developing a plan to execute the works to complete each phase of the project. The importance of the quality dashboard ensured that when handover of a section of works was panned, it was possible to demonstrate in advance that the works were completed to the correct standard.

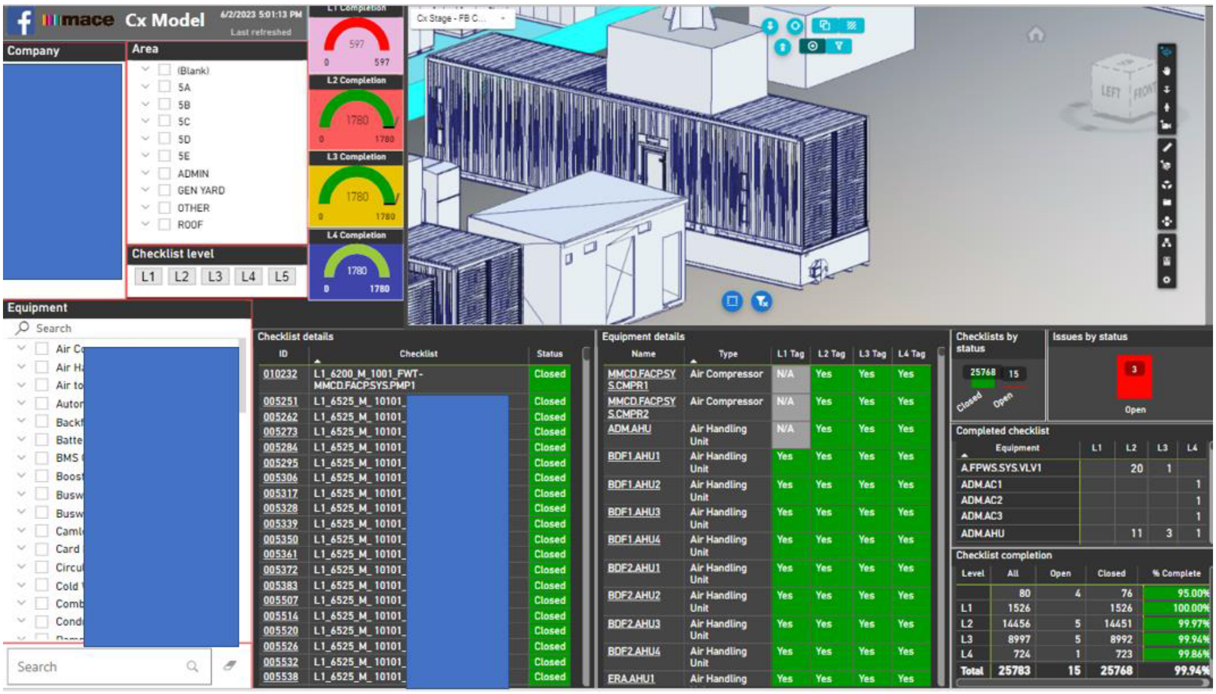

Figure 6: Progress Dashboard

FINDINGS

The use of digital tools was integral to the success of developing the Cx phase plan for a first of a kind mechanical cooling process. The construction and commissioning processes were integrated to achieve a successful project delivery. The ability to collaborate and generate near live data to track the elements of the project efficiently provided project teams the resource to make informed decisions.

Presenting complex project data in a form that allowed all stakeholders to engage effectively improved communication between project stakeholders. Near real time information increased the accountability of all stakeholders and increased the quality of commitments.

The use of collected field information provides certainty of the quality of the works. At each stage of the process the conditions of satisfaction were communicated, and the overall project performance was measured and displayed digitally. This provided the correct environment where transparency created trust and the digital information provided accountability against commitments. It was clear as the project developed that the complex nature of the Cx phase required greater co-ordination and involved multiple stakeholders to collaborate to complete.

This was particularly important in this phase as often specialist personnel would be required to be scheduled to be available weeks in advance of attending the project. This also gave assurances to all parties that the works were available and could be coordinated effectively. This was crucial to the success of this phase of the project. Specialist commissioning teams could be booked in to attend the project well in advance. The visibility and execution of make ready tasks increased the certainty of work being available for these teams when they arrived on site. This increase of resource utilization increased the productivity of the Cx phase of the project as commissioning could only continue when the preceding phase was completed. The use of near-live information and production dashboards allowed remote teams to collaborate effectively.

DISCUSSION

The forming of temporary alliances is typical in construction and the parties to these alliances change from the various stages from design to handover of construction projects. The social technical element provided by lean construction can develop the capabilities of the project by the process of continuous improvement.

New roles and responsibilities have been identified to support lean construction. Process facilitators assist collaborative meetings and now with increased digitization data management roles are important to manage the acquired data. Digital dashboarding were manged daily using technology syncing of acquired information for the digital control room and collaboration rooms. This support structure maintained the quality of the information that was increasingly relied upon for project status reporting and planning. It was important to the success of the project that all project teams could report information and communicate effectively.

The importance of using a single source of production and planning data positively influenced behaviours on the project. The quality of information collected from the field was high because it was used daily to inform operational meetings. The bottom-up communication stream integrated site teams and office teams which increased trust. The transparency of using shared dashboards improved accountability and allowed the teams to communicate effectively. The design and development of digital platforms and digital collaboration areas need to be considered to allow innovation and adaption of digital technology to support project production.

CONCLUSION

It is recognized that the adaption of Lean Construction 4.0 is driving innovation in the construction industry. This paper shows that building a digital environment to work effectively and interact with digital media virtually and in person promotes the adoption of digital tools. This in turn stimulates innovation and increases the use of digital tools to support construction management activities. The recognition of the role of digital in lean construction is important to note when identifying digital hardware and software to support construction management. Digital tools however cannot take the place of skilled workers and managers.

The creation of a lean production management system where tools and practices are supported by digital tools improves LC. The digital platforms were transparent, and the project status is visible to all stakeholders which in turn increases the collaboration and focus the deliver the project holistically.

There is an importance to ensure the quality of the data is correct. This requires multiple tools and constant maintenance of data. The coordination and collection of data to support managers is vital to the success of clarity of collaborative sessions both virtually and in person. The amount of information that can be collected is enormous. It is important to understand where the value is in the information and avoid overproduction of information that can over complicate and undermine the production control system.

The use of digital tools and platforms to effectively communicate and to demonstrate honoured commitments positively influences behaviours on the project. The flexibility provided by using digital tools, allows all stakeholders to engage and influence the workflow on the project. This improves the quality of engagement between project stakeholders where the acquired data forms the basis of the argument rather than a perception of how the project is progressing. This also encourages a holistic project continuous improvement process where stakeholders can continuously improve delivery and increases predictability of the project schedule.

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DEVELOPMENT OF AN IMMERSIVE VIRTUAL REALITY PROTOTYPE TO EXPLORE THE SOCIAL MECHANISMS OF THE LAST PLANNER® SYSTEM

Canlong Liu[1], Vicente A. González[2], Gaang Lee[3], and Roy Davies[4]

ABSTRACT

A successful implementation of the Last Planner® System (LPS) requires not only education on its principles, but also managing social mechanisms it brings up to reach outstanding outcomes. Simulation games have been widely applied to teach LPS principles, but they do not seem to appropriately capture the social mechanisms due to lack of socio-technical realism and inadequate gaming controls (i.e., control external factors other than one of interest). Immersive Virtual Reality (IVR) technology has the potential to reveal the LPS's social mechanisms by providing a highly-controlled and realistic simulation environment. However, how to effectively leverage IVR for LPS simulation is not well understood. In order to bridge this gap, we identified the essential elements that an IVR simulation should have to study the LPS social mechanisms. We then developed and tested a multi-user IVR prototype with the identified elements to simulate the LPS use in a "hypothetical" construction scenario. The results show that the prototype is feasible for studying LPS's social mechanisms. This study lays a foundation for future research in using IVR simulation games to study LPS social mechanisms.

KEYWORDS

Simulations, immersive virtual reality, Last Planner® System, social mechanism, collaboration

INTRODUCTION

Managing traditional construction projects is perceived as challenging due to the complexity of the construction environment, the interdependency of production processes, unreliable production pace, communication and coordination problems, antagonist organizational environments in projects, among others, resulting in uncertainty that negatively affects workflow reliability and project performance. Ballard (2000) pointed out that these problems in construction projects are exacerbated due to the traditional approach of viewing their production nature as a process of converting inputs into outputs, neglecting value generation and flow management. To address these issues, the Last Planner® System (LPS) has been introduced as a Lean based production planning and control tool. It intrinsically deals with the dual and symbiotic socio-technical nature of construction projects (Liu et al., 2020, 2022; Priven

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& Sacks, 2015). Technically speaking, the LPS deploys a robust methodological framework for production planning and control, which reduces workflow variability and uncertainty (Ballard, 2000). From another perspective, LPS can be seen as a social system comprised of project participants who work together to make plans and control project production (Ghosh et al., 2019). Therefore, social interactions among the project participants play a critical role in LPS implementation, improving project coordination and, thus, workflow (Ghosh et al., 2019; Priven & Sacks, 2015).

In spite of the increasing efforts to implement the LPS in the construction industry over the last 30 years, the comprehensive application of LPS principles on projects is still fragmented, and lagging behind (Ebbs et al., 2017; Priven & Sacks, 2015). Some studies have realized that this problem originates from the social-driven barriers: (1) Resistance to change; (2) Lack of cooperation, and technical-driven barriers: (3) Lack of understanding of LPS principles (Liu et al., 2020; Perez & Ghosh, 2018). Some researchers argue that the social and technical aspects associated with these barriers were not managed adequately in the past decades, impeding more effective dissemination and implementation of the team dynamics, LPS practices, knowledge in the construction industry (Gonzalez et al, 2015; Hamzeh 2011; Liu et al., 2020).

To achieve excellent implementation results, LPS requires not only effective implementation of tools and processes (Ballard, 2000; Ebbs et al., 2017) but also individuals to be motivated and empowered to complete teamwork in a highly collaborative environment (Kim & Rhee, 2020). Thus, studying and analyzing the project participant's social interactions, emergent psychological states, and their influence on enhancing positive teamwork, as well as how those behaviors seamlessly match the technical components of LPS, can bring valuable insight into realizing the full potential of LPS (Asadian & Leicht, 2022; Liu et al., 2022).

LPS SIMULATION GAMES

Simulation games are a hybrid of games and simulations that aim to train, educate, and entertain players while simulating the context of social system (Klabbers, 2009). Simulation games are often regarded as valuable in the Lean Construction industry because they offer a clear, realistic, and straightforward way of imparting knowledge about various Lean concepts. (Bhatnagar et al., 2022).

On the other hand, simulation games can be used to explore the social psychological phenomenon (McFarlane, 1971; Yiannakoulias, 2022). For instance, some simulation games are designed as digitalized environments, making data collection easier and allowing researchers to manipulate and control the experimental environment where hypotheses can be validated by manipulating specific variables (Lukosch et al., 2018). Simulation games can also create a situation or context through their sequence-specific rules or game controls, making it easy to elicit the participant's response to that situation (e.g., project teams may need to decide on adjusting plans when facing construction constraints). Also, it allows researchers to easily develop a coding or measuring approach based on these sequential rules that determine the specific behavior of game users (Lukosch et al., 2018; McFarlane, 1971). In addition, they allow researchers to replicate the same experiment multiple times without having to change the experimental design or set-ups (Lukosch et al., 2018). Therefore, simulation games have the potential to analyze the social mechanisms of LPS by evaluating individuals' behavior and psychological responses to controllable stimuli or scenarios.

There has been a growing interest in adopting Lean simulations and games in Lean academia and community (Bhatnagar et al., 2022). Several Lean simulation games teach different LPS principles through hands-on activities, such as building a schematic house with Lego™ bricks, to show the benefits of LPS compared to traditional management. The most popular training method is the commercial product LPS-based Villego game, which teaches LPS through two round games in a day (Warcup & Reeve, 2014). Another example is LEBSCO (González et al., 2015), which provides quick LPS training in a classroom setting, and COLLAPSE, a digital simulation game that requires users to complete LPS-related activities on spreadsheets (Raghavan et al., 2018). These engaging games, particularly Villego, make LPS knowledge more accessible to participants.

However, these games are not suitable for uncovering social mechanisms and generalizing findings to real-world settings, which is essential to devise practical intervention strategies for changing their social cooperation accordingly. There are four reasons. Firstly, the sense of presence in the tasks and contexts is too weak for users to perceive and act as a social self (for instance, COLPLASSE uses spreadsheet templates to simulate the operation of the project with an abstract environment) or over-complicated to play (for instance, Villego, which is a highly intricate simulation game requiring an in-depth understanding of LPS concepts and following rules, leading some people to lose their interest in participation). Secondly, they have inadequate gaming controls associated with the LPS principles and procedures. The successful running of the existing simulation games relies on the facilitator's intervention and the participants' accurate understanding of the rules. For instance, analyzing behavior responses from inconsistent experimental controls among groups is difficult when players break the rules and deviate from the LPS workflow. In other words, researchers are less likely to isolate extraneous effects that are irrelevant to social mechanisms, hindering the reproducibility and validity of results. Thirdly, they normally need physical models and additional set-up times, which hinders large-scale experiments. Fourthly, these games are designed for collecting the technical indicators of LPS implementation, such as PPC, time, cost, and knowledge uptake, but not for social indicators emergent during LPS-based teamwork.

IMMERSIVE VIRTUAL REALITY

Immersive Virtual Reality (IVR) involves computer-generated virtual environments with high visual impact and immersion levels, leading to increased engagement and perception (Feng et al., 2018). Thus, IVR can elicit targeted behavior using artificial sensory stimulation, even when the user is unaware (Lavalle, 2017). This virtual environment allows participants to feel as if they were physically present, and the high level of realism can make it difficult to distinguish between the virtual and real worlds. Thus, users' behaviors and responses in IVR are likely to match their real work context (Lavalle, 2017). The ability to conduct behavioral research using IVR offers numerous opportunities (Feng et al., 2018). In particular, a multi-user IVR has gained attention among researchers due to its capability to simulate social interactions in a realistic manner, for instance, where individuals can engage with either a virtual agent or another real person. Therefore, multi-user IVR environments are rapidly becoming popular in the fields of social behavioral and psychology studies. This is due to the flexibility of these environments in investigating and analyzing social cognition and social stress in psychological experiments (Bernard et al., 2018).

In this regard, we argue that there are several reasons supporting the use of IVR to address the limitations of existing LPS simulation games in conducting social experiments. First, its ability to edit the storyline (a collection of scenarios or events in which individuals can make decisions and act to advance the story's progression) and gaming controls have the potential to create the situation that researchers desire, which means the people are more likely to follow the game rules and procedure, making researchers obtain reliable results. Second, with the advent of cost-effective, portable, and networked-supported IVR head-mounted displays such as the Meta Quest 2, researchers can conduct large-scale experiments online to study the social mechanism of LPS.

On the other hand, by using IVR, researchers can obtain additional benefits for studying LPS social mechanisms that cannot be obtained from non-IVR simulation games. First, IVR enables individuals to behave as close to reality as possible (Feng et al., 2018), which has the potential to make the transferal of the simulation results to the real world more feasible. Second, with its high compatibility with biometric sensors and wearable instruments that participants can use during experiments, it has become easier to observe social behaviors and collect physiological data, such as galvanic skin response (GSR) and Heart Rate Variability (HRV). These features can provide a more robust result and help the researcher to gain a deeper understanding of social mechanisms of LPS.

Despite the potential of IVR technology to study the social mechanisms of LPS, there are still limitations to effectively integrating IVR functionalities and LPS principles into a simulation game to deepen the understanding of LPS. Specifically, at the preliminary stage, we do not know how to enable users to follow the LPS workflow using IVR-powered gaming controls. Additionally, we do not know how to design tasks and rules to create scenarios where social mechanisms can be captured. We also do not know what suitable technical solutions enable users to conduct teamwork, communicate, and finish tasks in the IVR environment. More importantly, we do not know how to enable researchers to collect behavior and physiological data in such an environment.

RESEARCH OBJECTIVES AND METHOD

As a preliminary step in filling the aforementioned knowledge gaps, this study aims to explore the viability of using IVR to create LPS simulation games, focusing on technical development. The purpose of developing the IVR simulation game is not for training but for experimentation, which opens doors to the broader use of IVR technology to conduct "controlled" Lean-driven social experiments. Specifically, the study aims (1) to explore the simplified LPS simulation workflow and rules, as well as related IVR prototype designs, and (2) to demonstrate the effectiveness of using IVR technology for LPS simulation games to explore the social mechanisms of LPS.

To achieve the objectives, bearing in mind the nature of the intended simulation game aimed to develop in this research, we first identify and determine the essential elements and rules that the VR-based LPS simulation should have. Then we developed the IVR prototype based on these findings. To test whether the developed IVR simulation game is feasible to study LPS's social mechanisms, we did "actually what" with a typical pavement task scenario. Specifically, it contains two testing rounds of the simulation case: traditional and LPS. We checked: (1) whether every user can complete their task and follow the procedure and rules using the proposed gaming controls; (2) whether our design in task dependencies and variations trigger social interaction among users; (3) whether the researcher can use this IVR prototype to conduct large-scale experiments and collect behavior and physiological data.

DEVELOPMENT OF THE IVR PROTOTYPE

CONCEPTUAL DESIGN AND GAMING CONTROLS OF THE IVR SIMULATION GAMES

The simulation games should have the ability to create a realistic and engaging setting allowing users to feel things like "it was a very meaningful experience" and respond to what they perceive as a realistic situation (Bhatnagar et al., 2022; Lukosch et al., 2018; McFarlane, 1971). We argue that IVR simulation games should offer users realistic construction scenarios and scenes to complete construction tasks. In this regard, the IVR environment should mimic real construction scenarios with 3D models, meeting areas, and construction sites. Second, The simulation game should find suitable navigation (moving around and exploring the virtual environment) solutions and interaction (communicating with people and interacting with virtual surroundings) solutions, allowing users to complete the tasks intuitively and realistically, as inappropriate navigation solutions may cause the motion sickness (Lackner, 2014). Third, cooperation and goal are important motivations that drive the users to complete tasks in the simulation games (Koivisto et al., 2018), so the IVR simulation games should allow users to make plans and complete construction tasks collaboratively, but limit their completion time. Fourth, the IVR prototype should simulate real-world construction and production systems. This requires users to perform key last planners, order materials in meetings and carry out tasks. In turn, the systems should respond to users' behavior like the real world (Lukosch et al., 2018). Sixth, the IVR simulation should have simplified rules and procedures, given that long duration and complex simulation rules are the major reasons for users' reluctance to participate in LPS simulation games (González et al., 2015). Lastly, to obtain better user experience and engagement, the IVR system should have a tutorial session to ensure every user can understand the game mechanism and goals.

On the other hand, simulation games should allow researchers to study social mechanisms by observing behavior and measuring psychological states. However, some social mechanisms are not easily found if users deviate from the rules. This requires the IVR system not only to allow the researcher to capture the social mechanisms but also to have gaming controls to create situations that induce these social nuances. Communication and decision-making are induced by dealing with uncertainty and task dependencies in construction management activities (Priven & Sacks, 2015). Thus, If a simulation game creates such a situation, the researcher can easily identify the emergent social mechanism. In order to identify these mechanisms, the IVR system must have a robust method to collect and analyze behaviors and psychological responses during the simulation. Therefore, the IVR simulation game should give users a level of freedom to finish tasks while also imposing dependency restrictions and uncertainty.

In order to study the social mechanism behind LPS, the prototype should provide two rounds of experiences (i.e., traditional and LPS) so that researchers can clearly see the social nuance when comparing the result of these two rounds. In that respect, it is necessary to determine the key principles and tools among traditional and LPS-based project teams, and design corresponding simulation rules and principles. Table 2 presents the LPS elements and devised rules in IVR simulation. It selected eight elements of the LPS based on Ballard's research (Ballard, 2000). The framework links the LPS elements and rules of simulation games to articulate the IVR design environment. In the traditional round, the LPS elements consider master scheduling, push planning, centralized decision-making, as well as the Planned Percent Complete (PPC) measure. In turn, the LPS-based round considers master scheduling, pull planning, constraint management, lookahead planning, commitment planning, distributed decision-making, continuous flow, and continuous improvement (discuss and analyze PPC). The implementation of these rules will be described in the next section.

Table 1: The LPS elements and devised rules in IVR simulation

LPS elements	**IVR simulation rules**	
	Traditional round rules	**LPS-based round rules**
Master scheduling	The manager released the plan	All users discuss the plan
Decision-making authority	Only manger	The manager along the other users develop the plan
Constraint management	Not applied	Users should discuss the constraints and remove them
Pull planning	The manager pushes the plan on others	The last planner can request resources when needed verbally and directly to the supplier
Lookahead planning	Not applied	Applied
Commitment planning	Tasks released by manager's requests	Tasks released by users' commitments
Continues improvement	Only PPC measure	Users should review and analyze the PPC.
Continuous Flow	Batch size is limited	The batch size can change if needed

SYSTEM ARCHITECTURE

Figure 1 depicts the architecture for a multiplayer IVR prototype designed to run both traditional and LPS-based rounds. It consists of a host acting as the researcher and clients. The prototype utilizes cutting-edge standalone wireless IVR headsets, Meta Quest 2, which offers a high level of mobility and a seamless match between users' movements and gestures in the virtual and real worlds (Meta, 2023). The controllers utilized in the prototype are wireless and do not require any additional tracking devices (the headset has integrated tracking sensors), providing users with the freedom to use them in any location. Also, the headset provides a casting function allowing users to share their IVR screen to a computer or smartphone. Wearable biometrical sensor sets: Shimmer3 GSR+ were attached to users' palms and ear to capture physiological data such as GSR, and HRV. The IVR prototype was created using C# programming language and the Unity game engine. Unity, a commonly used platform for creating desktop and VR video games and applications (www.unity.com), is compatible with the Meta Quest 2. Unity program provides basic modules to support the execution of the game. The login module defines the user identity by configuring the user roles and names; the production module provides the basic game mechanism that simulates the project lifecycle. The navigation and interaction model gives users a great degree of freedom to move, turn, and interact with the environment. The event module use a timer to measures and records the amount of time taken in a game. The timer has several timestamps or milestones associated with the pre-defined events waiting to be triggered. If a timestamp is reached, specific users will be notified and the environment will be influenced by the corresponding event. For example, suppliers will receive the notification of increasing delivery time, while global environment variables (e.g., delivery time) will be modified for all users. The network module provides an interface that synchronizes the local datasets to the cloud. All headsets are connected to a cloud server with Wi-Fi. Pun 2 and Photon voice (Photon, www.photonengine.com) are chosen as online hosting platforms, providing multiplayer supports. In addition, a researcher will join the network as a host by using a laptop with an Intel Core i9-10980HK processor, NVIDIA GeForce RTX 3080 graphic card, 32 GB of RAM, and a Windows 10 operating system. The host uses the Unity desktop editor to control the game, including starting and stopping the game, observing behavior, and accessing data from iMotions. The iMotion platform (iMotions, www.imotions.com) also operates on the laptop along with the game. It can read data generated by biometrical sensors wirelessly and capture headsets' screen.

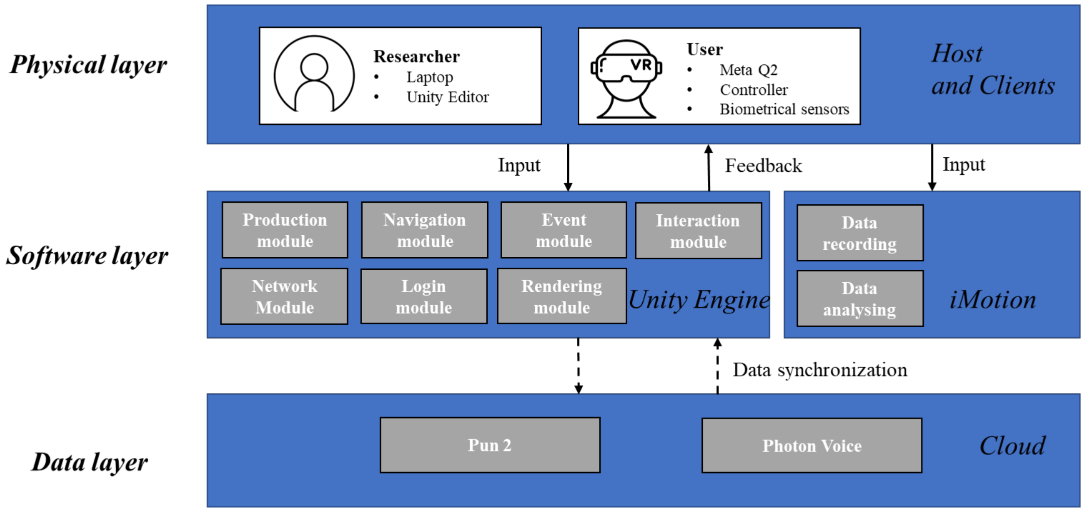

Figure 1: System architecture

IVR ENVIRONMENT

Four scenes and associated user interfaces have been devised in the IVR environment: (1) A Login scene enables users to use a virtual keyboard to enter a username, use a ray to select a role and different simulation scenes (see Figure 2a); (2) A Tutorial scene features an instruction board to provide game rules and guidance (see Figure 2b); (3) A Traditional Construction scene includes multiple sub-scenes: Construction, Production & Shipping, and Meeting & Planning sub-scenes (see Figure h). Figure (2c) shows that the users can control an embodied avatar. Figure (2d) shows that if the user presses the button, a ray will be cast from their hand to indicate the destination. Their embodied avatar will move the destination instantly after the user release the button. Figure (2e) shows the Meeting & Planning sub-scene is equipped with whiteboards, and users can use a virtual keyboard to make plans. The Production & Shipping sub-scene has a workstation for producing bricks and shipping them, allowing users to select the number of materials to be produced (see Figure 2f), while the Construction Site sub-scene has roadbeds where user can realistically use their hand to lay bricks and retrieve shipped bricks from pallets (see Figure 2g). (4) A LPS Construction scene is another scene that incorporates LPS procedures and tools into the production planning and control process of the project. It features similar sub-scenes and layout as the Traditional Construction scene, but with different rules and processes (e.g., the traditional Meeting & Planning sub-scene is replaced by a Lean-based Meeting sub-scene).

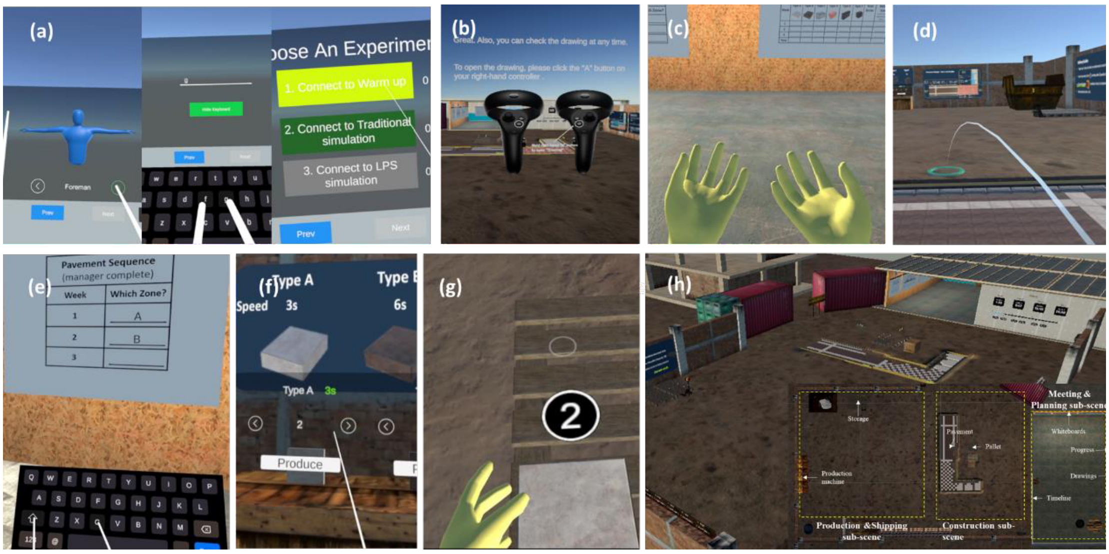

Figure 2: The user interfaces and scenes of the IVR environment: (a) A user selects roles, inserts usernames, and chooses simulation round; (b) A user read the tutorial boards; (c) A user has an embodied avatar; (d) A user moves to a position; (e) A user uses a virtual keyboard to make the plan (f) A user produce materials (g) a user grab materials (h) a construction simulation scene and a map.

PROTOTYPE TEST

TEST SCENARIOS AND STORYLINES

Hypothetical cases were created to test whether the architecture prototype presented in the "Development of the immersive virtual reality prototype for LPS simulation" section works as designed. In this hypothetical case, users must complete a pavement project (containing three different zones) within three weeks (simulated as 5 minutes per week in the IVR environment). This prototype should be played by three users maximum, including a manager, subcontractor, and supplier, which enables the exploration of the social interaction among key Last planners. Generally, the subcontractor is accountable for performing paving tasks at the construction site. The supplier is responsible for producing and delivering specific bricks to the subcontractors. The manager makes a plan and monitors the workflow. To achieve reliable gaming control, we use programming to restrict each role to only access its role-specific functions when performing tasks. Other than measuring and instruction before the game, the researcher does not provide cues or feedback to the users on the optimal way to complete the tasks. Before the game starts, all users will have a tutorial to learn how to interact with the VR environment and controls, as well as basic LPS procedures. Users must follow traditional (non-Lean) and LPS-based production planning and control approaches to complete the same tasks.

A simplified storyline was devised in this section, which presents a typical one-week simulation for all users. The IVR simulation has both the Traditional-based and the LPS-based construction rounds, which contain four main scenarios: Tutorial, Meeting & Planning, Construction, and Recap.

It is assumed that, in the beginning, users go through the Traditional round (see white blocks). Three users and a researcher meet for briefing goals and rules. In the Meeting & Planning scenario, the manager is responsible for compiling the plan (deciding on paving sequences, bricks production schedule, brick delivery schedule, and batch size). This simulates the Master scheduling and Weekly Work Plan (WWP) meetings. Once the meeting ends, the supplier and subcontractor are automatically taken to the production and delivery area and the construction area respectively to carry out the paving tasks. The supplier produces different types of bricks and delivers them in fixed batches, while the subcontractor executes the paving tasks. The manager is able to roam in all areas to monitor the project's progress and guide them to perform tasks. After the week ends, all players are immediately brought to the meeting area for a recap, where they discuss the previous week's outcomes, such as PPC, time, and quality. During this time, the supplier has notified the bad weather condition, and the supplier may report this issue to the manager. These processes will repeat three times (three weeks) to finish the project using the Traditional approach. After that, users will go through the LPS round. The workflow is similar to the Traditional round but has different planning and control rules and tasks (see the difference in Table 1). We envisaged that the researcher designates the traditional group as the control group and the LPS-based group as the experimental group, where the behavior and physiological data are to be collected.

TEST RESULTS

We illustrate the example screenshots of the demonstration case scenarios (see Figure 3a-e). Figure 3a shows that two users are controlling their embodied avatar and discussing the plan in the third user's view at the Meeting & Planning scenario. Users' positions and gestures have been synchronized with other users across the network. These features simulate a realistic social interaction environment, which could improve users' sense of presence during communication. Figure 3b shows the users' inputs on the commitment log, and the PPC register with automatically updated figures according to the planning status and the project progress. This information reveals the constraints among tasks, creating a situation where researchers can analyze social mechanisms by observing how users make decisions. In addition, their attendance in commitment analysis shows that users are able to complete the tasks following the procedure and rules (both traditional-based and LPS-based). Figure 3c shows an uncertain event is triggered and information (delivery time increase) pop-up on the supplier's screen, which provides a realistic situation in which the project team must address constraints. It also allows the researcher to compare the user's psychological responses to such situations in different experimental groups (e.g., compare each user's stress level between LPS and the traditional round in dealing with uncertainties). Figure 3d shows that the subcontractor has grabbed a brick and is placing it on the roadbed, while the manager is checking the time lapse on the timeline. The timeline shows that the second week is about to end, and all players will be brought to the meeting room to make a plan. The evidence suggests that the IVR system not only allows users to act on their own, but also has programmed gaming controls to ensure the simulation operates under the rules and procedures. Figure 3e shows that the researcher successfully uses the IVR system to observe behavior and collect GSR and HRV data during these situations. Notably, the behavioral and biometrical data can be aligned and streamed, which provides robust data collection methods for unpacking the social mechanisms.

Overall, the gaming control of the IVR prototype has the potential to enable robust experiment controls, thus ensuring the experiment's reproducibility, while time restrictions and few user requirements indicate its feasibility for conducting a large-scale experiment.

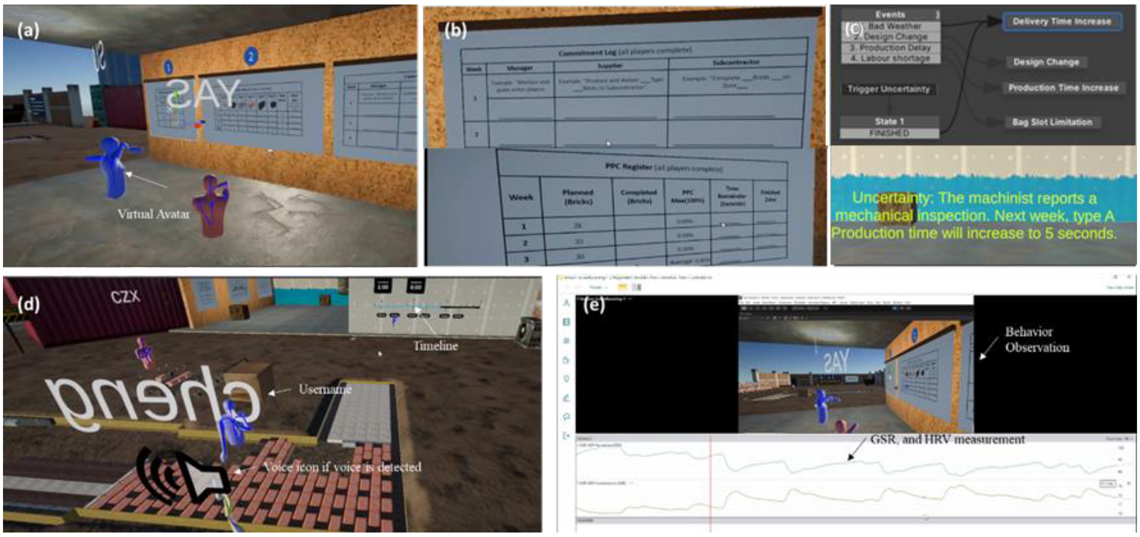

Figure 3: Screenshots of the demonstrative case and data collection platform: (a) During the Meeting & Planning scenario, a user interact with another user; (b) During Meeting & planning scenario, in the Meeting & planning sub-scene, users make the commitment plan, and analysis the PPC; (c) During Construction scenario, the system triggers uncertainties and impose the effect; (d) During Working scenario, in the Construction Site sub-scene, a user provide suggestions; (e) After the game, researcher code behaviors and analyses biometrical data.

DISCUSSION AND CONCLUSION

The purpose of this paper was to explore the viability and feasibility of using IVR to create LPS simulation games, with the goal of being able to develop methodologies to use these to better understand the social mechanisms of LPS. To do so, this paper determined the rules and essential elements of the IVR-based LPS simulation games. In this regard, this paper developed the IVR prototype, and illustrates a hypothetical case to demonstrate the realizations of these purposes.

The results show that the proposed IVR system is feasible for simulating the LPS and can improve our understanding of it by supporting the implementation of social experiments. This is due to its advantages in experimental control and support for large-scale experiments that involve the collection of behavioral or physiological data. The theoretical contribution lies in advancing Lean project management by providing a prototype design and data collection approach (containing technical requirements and design principles) that steps a stone for a new experimental avenue to study the social mechanisms of LPS. From a practical standpoint, using this IVR platform combined with gamification principles for purpose-training could improve the implementation of LPS in the construction industry. The use of IVR technology is not without limitations. (1) The IVR environment is a simplified representation of the LPS, only simulating a few technical and social dimensions of the LPS in real life. (2) ecological validity test of this prototype is needed before using it to conduct social experiments.

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LEAN CONSTRUCTION WASTE REDUCTION THROUGH THE AUTONOMOUS VEHICLE TECHNOLOGY

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ABSTRACT

In the automotive industry, autonomous vehicles (AVs) are an advanced innovation that has the potential to revolutionise the existing transportation system significantly. In addition, AVs provide benefits for society, the economy, and the environment. As far as Lean Construction (LC) is concerned, these features appear promising. LC's primary objective is to minimise the waste of resources, time, and effort. This study examines the potential contribution of AVs to LC through two exhaustive rounds of literature review. The research aims to establish the links between AVs and the overarching LC philosophy and principles. The first round of the literature review identified that AVs could reduce waste in three areas: inventory, transportation, and waiting time. Moreover, they can support solutions to environmental concerns. Additional literature reviews have identified five potential approaches for a new technology that can be applied to the construction industry to enhance the implementation of AVs. As well as the anticipated developments in each case are discussed accordingly. The practical implications of the findings are that AVs can reduce waste and cost, increase efficiency and productivity, and help create a more sustainable construction industry. According to the study, the construction industry should take a proactive approach to implementing AVs.

KEYWORDS

Lean construction, AVs, transportation, waste

INTRODUCTION

The fully advanced autonomous vehicles, known as driverless cars, are capable of identifying their surroundings by increasingly dependent on sophisticated technology to replace the actual human driving tasks, decisions, and behaviors (Ma et al., 2020). It is able to travel independently to various locations while excluding any human driving assistance (Litman, 2017). In fact, the Society of Automotive Engineers (SAE) has developed the SAE international standards J3016, which illustrates the AV's six categories, starting from the most basic (nonautonomous) to the most advanced vehicle (fully autonomous) (SAE International from SAE J3016™, 2021). This

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innovation offers a major breakthrough in the existing transportation system to benefit society, the economy, and the environment. It also offers improvements in automated driving-assist characteristics and capabilities with enormous advantages for the AV lower levels (Katrakazas et al., 2015; Le Vine et al., 2015).

It is anticipated as a realistic solution for future transportation that will increase traffic efficiency, decrease fuel consumption, and importantly reduce carbon dioxide emissions, to name a few. It is, also largely relies on a computerised system equipped with advanced technologies that have been built inside the vehicle (Parkin et al., 2018). Furthermore, it may communicate traffic information among cars through advanced communication equipment utilising advanced Internet Technologies (IT) via a cloud service. Additionally, super-fast communication technology between cars that are based upon the Fifth Generation (5G) network to improve its vision in a fully secured manner (Storck & Duarte-Figueiredo, 2020). Vehicles are considered the heart of land transportation, as well as play a vital role in the construction industry. However, transportation has been identified as one of the leading waste types in the LC. It, therefore, requires more collaborative efforts to minimise its impact on society, the economy, and the environment. Also, to achieve the fundamental philosophy and principles of lean construction.

Lean construction (LC) presents "a way to design production systems to minimize waste of materials, time, and effort in order to generate the maximum possible amount of value" (Koskela et al., 2002). Lean construction recognises eight types of waste in the construction sector (Aziz & Hafez, 2013; Koskela, 2004; Sarhan et al., 2017) as follows:

1- Overproduction: Linked to the creation of a larger volume than requested or earlier than desired, which results in a waste of work efforts and materials.

2- Substitution: Financial waste produced by the replacement of a less-priced product with a more costly one, easy duty performed by an over-skilled individual, or the use of extremely advanced technology for simpler jobs.

3- Waiting time: Related to idle time resulting from a shortage of material supply chain coordination and levelling, as well as the speed of activity by subgroups or equipment.

4- Transportation: The internal materials flow in construction sites could result from improper handling, the application of insufficient machinery, or poor passage conditions. It has the following significant consequences as loss of manpower, energy, storage area, and potential material loss while transfer.

5- Processing: Associated with the processor (conversion) operation, which can possibly be prevented by adjusting building technology.

6- Inventories: Relating to overstocks or unused stockpiles that cause waste of materials.

7- Movement: Deals with activities performed by employees that are needles in the workplace.

8- Production of defective products: It occurs when the final result fails to fulfil the quality standards.

As indicated earlier, the AVs provide enormous features that could boost the entire land transportation sector. However, transportation has been identified as one of the main waste types in the LC. Therefore, the research aims to explore the links between the use of AVs and LC fundamental philosophy and principles, which might offer a significant waste reduction in some of the earlier identified and widely agreed areas. This could consolidate the LC philosophy and support its concepts overall. Nevertheless, AV technology is still in its infancy stages of development, and studies that provide information on this matter are lacking. By examining the potential contributions of AVs in the LC industry, this study seeks to identify any further potential reduction in the LC waste types through the deployment of AV innovation. It also provides five different approaches to assist the decision-makers in deploying the AVs based on their risk assessments (on a governmental scale) in order to maximise their value in lean construction.

METHODOLOGY

Using a two-stage research design, this study investigates how AVs can contribute to lean construction, as shown in Figure 1.

In the *first phase*, a comprehensive literature review was conducted to identify the current state of the art in autonomous vehicle features, as the research parameter has been selected to search the “autonomous vehicles" AND "technology features" terms in google scholar to end up with 337 articles ranging from 2015 to present. Furthermore, the research team has analysed the identified articles based on AV aspects that could contribute to the reduction of waste recognised by lean construction to end up with 23 related articles. By utilising this information, the team developed comprehensive analogies linking the prominent features of AVs with the purpose of lean construction in order to reduce waste.

In the *second phase*, a literature review was conducted to identify existing strategies that could be used to support the application and utilisation of AVs in construction supply chain management. A set of keywords of "Autonomous vehicle" AND "deployment strategies" has been searched on google scholar from 2015 to date to end up with 260 related articles. It led us to identify common strategies for the application of AVs. Based on the results of the second literature review round and the best practices reported, we have identified a comprehensive set of guidelines that can be applied to the construction industry to assist in the implementation of AVs. These guidelines provide an outline of the necessary steps to be taken in order to successfully incorporate AVs into construction supply chain management based on the situation and risk acceptance level by the industry. They should be used to ensure the successful adoption of these vehicles and ensure that the full potential of their use is realised.

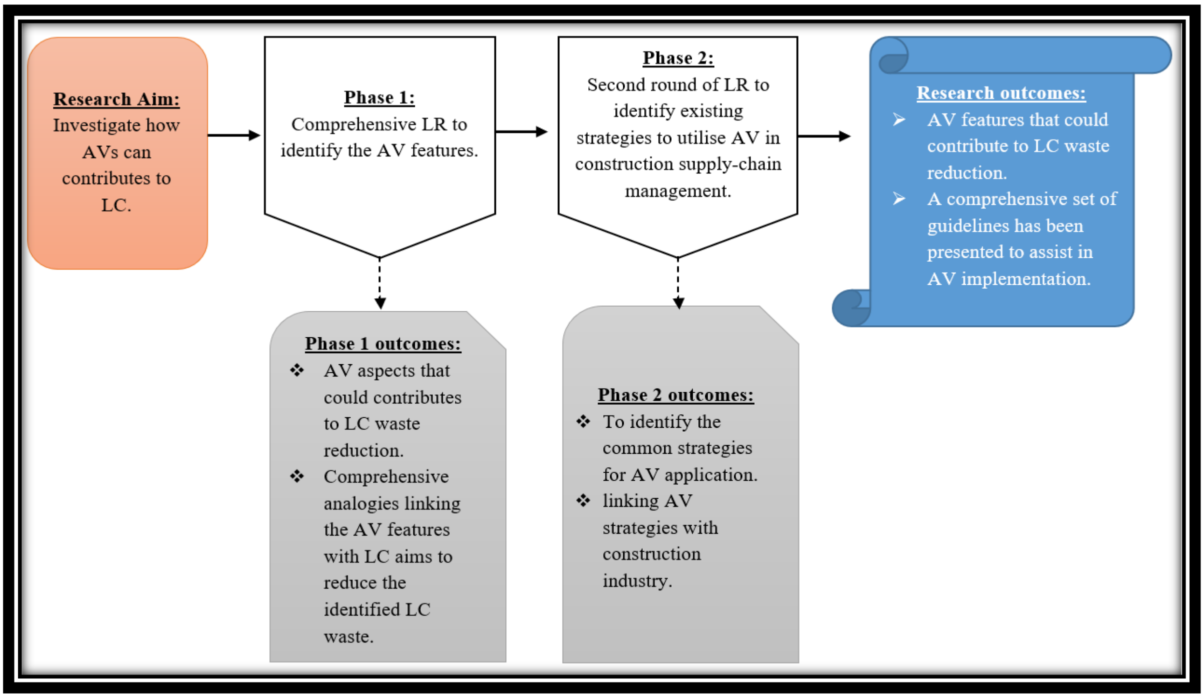

Figure 1: Research Outcomes

AVS AND THEIR STANDARDS

AVs or driverless vehicles are laying the foundation for future sustainable transportation (Chehri & Mouftah, 2019; Owais et al., 2022; Zou et al., 2021). It has the ability to navigate to numerous locations while responding quickly to signs, humans, and animals. It is also capable of overcoming unexpected obstacles independently (Greenblatt, 2016; Xing et al., 2021). The AV is anticipated to reduce transport emissions, vehicle journeys, and occupied road vehicles by 66, 30, and 28 per cent, respectively (Namboodiri, 2018). It could, also, reduce parking spots by 44 per cent and up to 87 per cent of road accidents. Therefore, the emergence of AVs could offer several benefits for society, the economy, and the environment.

It is predicted, for instance, to boost road capabilities by up to 100 per cent to accommodate more vehicles on the roads and smooth traffic patterns by up to 20 per cent, reducing unnecessary expenditure, fuel consumption, and time waste on the roads (Sundquist, 2016). Besides, it is expected that up to 75 per cent of fully driven AVs will occupy the roads by 2040 (Luttrell et al., 2015). Moreover, AVs are predicted to have around 70 per cent impact on large transportation vocations in the US and Europe by 2030 (Baratta, 2021). Researchers estimate that five per cent of this innovation would be expected to improve road congestion associated with stop-and-go behaviour, which would result in a 60 per cent reduction in transport emissions (Stern et al., 2018). Resulting in timesaving for people, and a decrease in the vehicle journey period on the roads, which will greatly reflect on transportation emissions.

As humans constantly depend on advanced technologies to replace traditional driving techniques and unexplained human driving behaviours, AV innovation could be a novel solution since they are able to assess their environment and proceed accordingly (Ma et al., 2020). Furthermore, despite the necessity of human participation in traditional driving tasks, AV could fully replace traditional driving to increase human efficiency in other activities (Litman, 2017). Therefore, the Society of Automotive Engineers (SAE) global standardisation J3016 has been issued aiming to define the six AV layers (SAE International from SAE J3016™, 2021-04-30). Starting with the least sophisticated layer, which requires the full involvement of the driver (nonautonomous), and proceeding up to the most sophisticated layer, which excuses the driver from duty (fully autonomous). These global standardisation levels had "become a de facto global standard adopted by stakeholders in the automated vehicle technology", in 2018 (Hopkins & Schwanen, 2021). Therefore, the SAE international standards aimed to illustrate the AV levels to aid in embracing the technological revolution and assist the deployment of AV locally.

WASTE REDUCTION THROUGH THE USE OF AVS

The adoption of AVs allows lean construction to further enhance one of its main objectives associated with waste reduction/elimination. It can lead to increased efficiency and productivity in the construction industry, as well as an environmental impact reduction. According to our analogical analysis, three primary waste categories could significantly benefit from automated vehicles:

1- **Inventory waste:** It presents a common waste in the construction industry and a challenge for lean construction practices (Ansah et al., 2016). It is the goal of LC to reduce waste by keeping inventory levels low, and ordering only what is required when the need arises. This goal is challenged by the risk of inadequate supply on-site, burglary, degradation, and material damage (Aziz & Hafez, 2013). To prevent these challenges, in the construction industry, it is often necessary to order materials in advance and in excess to ensure that they are available when needed. This excess inventory takes up valuable space, ties up capital, and increases the risk of obsolescence (Lim YenWui et al., 2009). Therefore, the collaboration between advanced automotive technology and lean construction could help reduce excessive inventory problems as a type of construction waste by facilitating inventory management and reducing uncertainty around resource availability. Also enables the accurate tracking of resources in real-time and improves delivery times.

Improved delivery: The use of AVs, such as advanced driverless trucks, can improve the speed and accuracy of delivery and reduce the uncertainty surrounding the delivery of materials and equipment (Teoman, 2020). With autonomous vehicle delivery, there will be no need to keep excessive inventory in storage, which can be costly and inefficient as identified as one of the waste types in LC. This ultimately leads to significant cost savings and operational efficiency, as well as improved customer satisfaction with faster and more reliable deliveries.

Better tracking: By utilising autonomous technology, materials, and equipment can be tracked from the supplier to the construction site, providing a more accurate picture of what materials are available and where they are located through the Internet of Things (Liu et al., 2019). As a result of collaboration with AVs, losses, damages, and materials are minimised, and unnecessary lead times are avoided, which results in improved project outcomes and enhanced cost efficiency.

2- **Transportation waste:** AVs can play an instrumental role in reducing transportation waste by providing more efficient, safe, and sustainable solutions. In addition to the improved delivery schedules discussed in the previous item, AVs may also contribute to further reduction of transportation waste in several ways, including:

Increased capacity: AVs have the ability to operate 24/7 without the need for rest breaks, allowing more materials to be transported in a shorter amount of time. Additionally, they can be used in hazardous conditions where manual drivers cannot operate (Teoman, 2020). They can also be used to transport large amounts of materials in one trip. Furthermore, they can be operated more efficiently than manual drivers, resulting in fewer trips and better materials delivery (Heutger & Kueckelhaus, 2020).

Enhanced safety: AVs can reduce the number of accidents on the job site, minimising the risk of injury to workers and reducing the potential for delays (Fagnant & Kockelman, 2015). AVs use sensors and cameras to detect their environment and navigate around obstacles (Parkin et al., 2018). This eliminates human error and increases safety by ensuring that the vehicles are operating in compliance with safety regulations independently.

Lower emissions: AVs can be designed to be more energy efficient than conventional vehicles, thereby reducing their carbon footprint and the overall impact of transportation on the environment (Massar et al., 2021). AVs use advanced navigation and control systems that allow them to optimise their routes autonomously, resulting in less wasted energy and fewer emissions (Weimerskirch & Dominic, 2018). At any point in time, the AVs engine must use an efficient design because their need for efficiency in the engine is driven by timeless concerns such as environmental sustainability, resource scarcity, economic benefits, and technological innovation. As autonomous vehicles remain a relatively younger technology, they keep offering significant opportunities for innovation and advancement. By improving the efficiency of engines and powertrains, manufacturers can develop new and innovative technologies that can further improve the performance and efficiency of AVs, which further contributes to emission waste reduction.

Better coordination: AVs can be integrated with other management systems, such as construction supply chain management, allowing for real-time monitoring of delivery schedules and reducing the potential for bottlenecks or other delays (Sharm, 2022).

3- **Waiting time:** This is another challenge in the construction industry and presents a major waste source as discussed under LC (Lim YenWui et al., 2009). It can result in higher costs, reduced efficiency, and decreased overall project productivity (McBride, 2003). Implementing AVs can contribute to the reduction of waiting time in several ways, including the following:

Reduce delivery waiting times: AVs can deliver materials to the job site more frequently and more accurately, decreasing the wait time for materials to arrive, and cutting logistic costs (Xiaosheng & Hamzeh, 2020). AVs are able to calculate the most efficient route to the job site independently and can travel non-stop, which reduces travel time. Also, as time passes and technology becomes more accessible, the cost is expected to reduce. In addition, AVs do not require a human driver to operate the delivery vehicle. Therefore, the driver could be relocated to another construction site activities to increase construction performance and reduce unnecessary expenditure. For instance, driver expenditures account for a significant portion of total freight journey expenses, accounting for approximately 40 per cent of truck operational expenses in a high-wage nation (Engholm et al., 2020). The logistic cost might be significantly decreased through autonomous vehicles.

Improve equipment utilisation: AVs can be used to transport equipment between job sites, reducing the wait time for equipment to be available on a specific job site (Gružauskas et al., 2018). AVs can provide a continuous flow of equipment to job sites, allowing for faster completion of projects. Furthermore, AVs can reduce the amount of manual handling of equipment which can lead to fewer accidents and improved safety.

Streamline transportation: AVs can be programmed to follow the most efficient route so that less time is lost in traffic or on non-optimised delivery routes (Namboodiri, 2018). Autonomous vehicles have access to more advanced mapping and navigation techniques. Companies like TomTom are making automated driving more comfortable, efficient, and safer by offering technology that aids AV planning in advance and acts as a security net for sensors whenever vision and situation are unacceptable (Strijbosch, 2018). TomTom’s technology is scalable and cost-effective, seamlessly integrating with internal systems, and currently powers autonomous driving for leading car manufacturers. Besides, Nvidia has also introduced its latest mapping platform, providing the AV sector with accurate mapping that covers more than 300 thousand miles of highway in Asia, Europe, and North America (Bellan, 2022). Moreover, they are equipped with a range of sensors, cameras, and other technologies that enable them to detect and avoid obstacles in real-time (Parkin et al., 2018). This means that they can make on-the-fly route adjustments to avoid traffic congestion or road closures, without requiring any input from the driver.

Enhance coordination: Through the use of IoT, AVs can be integrated with other construction management systems, enhancing coordination and reducing the risk of bottlenecks (Sharm, 2022). With the use of IoT technology in AVs, it is possible to keep track of a number of different aspects of the delivery process. These aspects range from loading and unloading to the route taken and the arrival schedule of the delivery without the requirements of manual updates. This data can be used to reduce the risk of delays or bottlenecks.

Besides increasing productivity and efficiency, automated vehicles can also be environmentally friendly. Despite the LC philosophies of "respect for people", "maximizing value while minimizing waste", and "continuous improvement" (Do, 2022), sustainability and lean methodologies tend to clash whenever the supply chain is geographically expanded and participates in carbon dioxide emissions (Sertyesilisik, 2016). As the research aims to assist lean construction in achieving one of its primary objectives, namely reducing and eliminating waste, AVs can also help LC to address environmental concerns as well. After illustrating the AV benefits and how collaboration with LC could aid to support its core philosophy, it is crystal clear that waste reduction could be achieved through AVs. This can provide tremendous value to the environment, the economy, and society as a whole.

STRATEGY TO IMPLEMENT AVS IN THE CONSTRUCTION INDUSTRY

Previously, it has been discussed how AVs can assist the construction industry in achieving LC objectives if they are adopted by this sector. For AV to be successfully adopted at the industrial level, it must be accepted at a higher governmental level. Nevertheless, many developed countries have not fully implemented AV due to unforeseen long-term risks such as safety, liability, and cyber security (Milakis, 2019; Taeihagh & Lim, 2019). Essentially, autonomous technologies are widely acknowledged for their benefits, but questions are raised about their deployment, hazards, and unanticipated outcomes (Taeihagh & Lim, 2019). In fact, several scholars have admitted that the adoption of new technology would surely result in some unexpected risks (Taleb, 2007; Clarke, 1999). These risks frequently result in major expenditures for the interested parties (Perrow, 1999). Therefore, safety, liability, and cybersecurity as risk factors remain significant challenges for the industry to adopt such innovation.

To overcome these challenges, five AV-related governing approaches are presented by Li et al. (2021), and Li et al. (2018), which define the potential scenarios when deploying new technology. The governance measures that decision-makers may use to manage risks associated with the deployment are intended to achieve optimal user advantages while reducing technology-associated risks. For this scenario, the proposed approaches for deploying AV innovation in the construction industry are presented as follows:

- **Adaptation-oriented:** The industry can be more flexible if it accepts uncertainty and enhances its ability to handle disturbances. This approach integrates the factors of collaborative responsibility, long-term strategy, and co-decision (Li et al., 2018). This technique aims to develop strategies to cope with uncertain events. It is similar to resilience and adaptive resilience developed by Nair and Howlett (2016) and Walker et al. (2012). The construction industry can use this approach to create plans that are flexible and can be adjusted to changing conditions arising from the adoption of AVs. This allows the industry to stay ahead of potential risks and remain competitive. Construction organisations can also make better decisions and improve service quality by collaborating among stakeholders with this approach. However, some may argue that this approach is not fool proof. What if the conditions change too rapidly for the organisation to keep up? What if stakeholders do not agree on a course of action? These are valid concerns that should be considered before adopting this approach.
- **Toleration-Oriented:** The approach’s main objective is tolerating risks. Operational decision-makers are in charge of inspiring the industry to perform efficiently in a constantly changing environment in light of the adoption of AVs (Nair & Howlett, 2016). On the other hand, this approach may not be the most effective. Tolerating risks can lead to more accidents and injuries, which is not ideal for either the industry or the public.
- **Controlled-Oriented:** This strategy is focused on the prevention of future accidents by providing employees with training and knowledge that will empower them to make

better decisions. It also emphasises compliance with laws and regulations, as this will help ensure that risks are managed appropriately. Furthermore, by using realistic risk estimations, the organisation can ensure that its risk assessments accurately reflect the current risk level. (Krieger, 2013). A focus on compliance, however, has been argued by some experts to cause more accidents. Organisations often create rules and regulations that are too restrictive when they focus on compliance. Thus, compliance-focused strategies may actually result in more accidents than those that would otherwise occur. Consequently, employees may take shortcuts or take risks that they would not otherwise take.

- **Prevention-oriented:** Decision-makers implementing AVs use this defensive strategy to reduce their associated hazards (Li et al., 2018). Nevertheless, its slow response time makes policy meaningless. As a result, it is important to invest in more rigorous safety measures and driver education to ensure that AVs are used safely and responsibly.
- **No-Response:** The hazards are not addressed by decision-makers due to the low level of knowledge about AVs and their abilities (Walker et al., 2010). Consequently, decision-makers often overlook the potential threats of autonomous vehicles, resulting in inadequate safety policies.

A variety of these five governing approaches can aid decision-makers in selecting the appropriate approach during the implementation phase. Depending on the environment, one approach may be more cost-effective, while another may be more expedient. One approach may also be more sustainable, while another may be more appropriate for a particular environment. Each of the five AV-related governing approaches must be carefully analysed before implementation to maximise AV benefits while minimising risks in the construction sector.

CONCLUSION

It has been shown that AVs offer a wide variety of benefits, including improved safety due to the absence of human error, improved fuel economy, and reduced congestion. Furthermore, it provides a convenient alternative to traditional transportation modes, in addition to providing new employment opportunities in the development and maintenance of automated vehicles and other activities. The purpose of this study was to examine the potential contribution of AVs to the waste reduction goal of lean construction. The contributions were categorised into three groups: Inventory waste, which can benefit from the ability of AVs to offer improved delivery and better tracking; Transportation waste, which can benefit from the increased capacity, enhanced safety, lower emissions, and enhanced coordination offered by AVs; and Waiting time, which can be reduced by improving equipment utilisation, streamline transportation, and improving coordination among activities.

Also, AVs can help LC address environmental concerns. Furthermore, the paper discussed potential strategies for implementing AV technology within the industry. A discussion of five possible scenarios was provided, including adaptation-oriented, tolerance-oriented, control-oriented, prevention-oriented, and no-response scenarios. This study contributes to the knowledge base by providing an analysis of the potential contributions of AVs to LC waste reduction. Additionally, the examined scenarios in this document aimed to enhance the implementation of AVs in the construction industry to support the decision-makers in selecting the most suitable approach during the implementation phase. The practical implications of the study suggest that the construction industry should take a proactive approach to the implementation of AVs. This is especially true in light of the anticipated environmental benefits and cost savings. These conclusions are made based on an exhaustive round of literature review however future research may involve different chains of keywords and different databases.

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EFFICIENT PAVEMENT DISTRESS DETECTION AND VISUAL MANAGEMENT IN LEAN CONSTRUCTION BASED ON BIM AND DEEP LEARNING

Ting Deng[1] and Yi Tan[2]

ABSTRACT

With a wide range of road construction worldwide, the focus of road engineering has shifted to road maintenance and management. This paper presents a research aimed at developing a lean management framework that integrates BIM and deep learning technology to guide lean production applications in road maintenance management. Firstly, the pavement distress dataset is established based on the obtained road point cloud data. Secondly, a deep learning-based 3D object detection network is applied for automatically detect the pavement distress and improve the accuracy and reliability of the detection. After obtaining the detection information of the distress, Dynamo is utilized to realize the efficient visualization management of pavement distresses. Finally, an untrained road section is applied for the experiment. The predicted information of distress is integrated and visualized in BIM model can provide a better maintenance guidance and well promote the transformation of pavement intelligent maintenance management.

KEYWORDS

Lean construction, template, formatting, instructions, references.

INTRODUCTION

Infrastructure maintenance is crucial for ensuring the safe and efficient functioning of roads, bridges, and other structures. For example, as large-scale roads are built and operated over time, there will be exhibited a range of distresses, including cracks, potholes, and so on. These distresses may directly reduce the driving comfort and safety (Zhong et al, 2022), affect the performance and normal service life of the road, and even lead to serious traffic accidents. Therefore, it is significant to detect the pavement distress efficiently and accurately for the pavement maintenance.

Traditional pavement distress detection methods include manual inspections, visual assessments. However, these methods are often time-consuming, labor-intensive, and may be not able to provide the detailed information for making accurate evaluation. To improve the efficiency and reliability of pavement distress detection, the concept of lean construction is introduced. Lean construction is an approach that focuses on reducing waste, streamlining processes, and improving efficiency. This concept is particularly important in the pavement

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distress detection and management process for more efficient analysis of road pavement conditions. In fact, with the development of computer vision technology, there has been a significant amount of research on image-based pavement distress detection over the past few decades. This automated pavement distress detection technology can greatly improve the efficiency and accuracy of distress detection. However, image-based road data lacks depth information and cannot clearly express the spatial relationship of pavement distress.

With the cost reduction of 3D data acquisition devices, 3D laser scanning technology has gradually become an important ways of road data acquisition. The 3D point cloud data collected by this technology can obtain the depth information of pavement, and is not easily affected by the environment, making it an effective data source for improving the accuracy and reliability of pavement distress detection. Although some 3D data-based pavement distress detection algorithms (Guan et al, 2021; Huang et al, 2014; Jiang & Tsai, 2016; Li et al, 2017; Ouyang & Xu, 2013; Zhang, Wang, et al, 2017a, 2017b) have achieved certain success in recent years, most of these methods convert point cloud data into other forms and do not fully leverage the advantages of point cloud data. On the other hand, point cloud-based object detection algorithms have been widely used in fields such as autonomous driving and have achieved good results. However, at present, point cloud-based object detection is mainly tested on some public large-scale datasets [30], and has not yet been implemented in pavement distress detection task. In addition, there is limited research on effectively managing distress information by further connecting detected road distresses to the real world.

Therefore, in order to directly apply 3D point cloud data to automate pavement distress detection and improve the lean effectiveness in road maintenance, this paper proposes a framework that integrates lean management into pavement distress detection and visualization management based on 3D laser point cloud data, deep learning methods, and BIM. The proposed method aims to automatically detect pavement distress through deep learning methods to improve accuracy and reliability, and then visualize the detected results in BIM environment to improve management efficiency.

This paper is organized as follows. Section 2 reviews the literature of lean concepts, pavement distress detection, and BIM-based pavement maintenance management. Section 3 introduces the detailed information of the proposed method. Section 4 used an experiment to demonstrate the applicability of the proposed method, and finally, Section 5 has the conclusions and future work.

RELATED WORKS

LEAN CONCEPT IN THE CONSTRUCTION INDUSTRY

The principles of lean thinking are based on the lean production philosophy originated by the manufacturer Toyota and developed under the guidance of engineer Taichi Ohno(Howell, 1999). The underlying philosophy of lean production theory is to minimize costs, materials and time(Anandh et al, 2021), and evaluate working practice to eliminate unnecessary activities while preserving or increasing value(Chen et al, 2012). The idea of Lean concepts originated in the manufacturing industry, but have since spread to the construction industry. At first, the goal of lean construction was to apply manufacturing principles by standardizing processes. However, practitioners and researchers soon discovered the dynamic nature of construction project management and adapted their approach to fit the unique requirements of each stage of the project(Hamdar et al, 2015). Shou et al (2021) develop a lean management framework for guiding lean production applications in the oil and gas industry. Forbes et al. explored the management of roadway safety from a Lean perspective and put forward methods to prevent accidents and eliminate related wastes(Forbes & Ahmed, 2010).

The purpose of Lean Construction (LC) is to eliminate non-value adding activities, also known as waste, in construction projects and increase the value for relevant parties. The implementation of LC principles can result in substantial improvements in road maintenance projects where the impact of delays can be severe and affect all parties involved. Despite this, traditional approaches in infrastructure asset management have yet to fully embrace lean thinking in their planning for road maintenance (Mohammadi et al, 2022). Therefore, this paper combined lean principle to improve the pavement maintenance in distress detection and visualization management.

PAVEMENT DISTRESS DETECTION USING INNOVATION TECHNOLOGY

Traditional method of manually detecting pavement distress is time-consuming, inefficiency, and low accuracy. With the amount of pavement maintenance continues to increase, there is a significant need for automatic distress detection technologies which can improve the detection efficiency and accuracy. (Zhong et al, 2022). Over the past decades, there have been various researches focused on image-based pavement distress detection. Traditional approaches for pavement distress detection using image algorithms include edge detection-based methods (Zou et al, 2012), threshold-based segmentation methods (Wang & Tang, 2011),et al. However, these methods are Those methods are greatly impacted by the presence of shadows and varying lighting conditions in images, leading to negative detection results.

In the past few years, deep learning-based methods have been extensively researched in pavement distress detection, particularly the deep convolutional neural networks (CNNs) (Zhang, Wang, Li, et al, 2017). These methods have proven that the CNNs to be more efficient and stable than other traditional machine learning detection methods. For instance, Li et al (2020) used a CNN-based method on 3D pavement images to detect pavement distress and demonstrated the suitability of CNNs in classifying defects on pavement images. However, the focus of these methods aimed at classifying of the pavement distress without location information. Therefore, object detection methods have been introduced to enable the precise estimation of distress features. Du et al (2021) used the YOLO network to predict both pavement distress category and location using the information from road images in complex environment. Ibragimov et al (2022) proposed a pavement distress detection method based on Faster R-CNN and applied it to a full-size pavement image framework which allows to reduce the sliding window size and enable to detect cracks in larger images. Despite the high accuracy achieved by existing image-based pavement distress detection methods, there are still some limitations. The detection effect is inevitably limited under complex road conditions such as varying light and shadows. Furthermore, pavement images lack depth information and unable to express the spatial relationship of distress clearly.

With the development of 3D laser scanning technology, it is easier to obtain road point cloud data. This kind of data is not affected by shadow and light, and also contains the depth information and can express the spatial positions and geometric dimensions (Medina et al, 2014). Several researches have explored the application of point cloud data for pavement distress detection. Zhang, Wang, et al (2017a) proposed a 3D shadow modelling method to transform the original point cloud data into binary images which combined with noise suppressing algorithms to attain the target descended patterns. Tan and Li (2019) have utilized road images from UAV oblique photogrammetry to reconstruct road 3D point cloud models. However, there methods either manually extract features or process 3D pavement data from a 2D perspective before applying 2D-based deep learning methods for distress detection. Therefore, this research attempts to directly utilize the 3D point cloud data for automatic pavement distress detection by using the deep learning method which can improve the detection accuracy and generalization capability.

BIM-BASED PAVEMENT MAINTENANCE MANAGEMENT

In recent years, the advancement of pavement inspection techniques has brought attention to the optimal solutions for data management. The traditional approaches of Pavement Management Systems are inadequate to exploit the potential of this information, particularly for visualization and infrastructure modelling (Bosurgi et al, 2021), which can be addressed by using BIM. In practice, BIM is widely used in the processes and activities of construction projects to improve the outcome of lean production, but its application during the operation and maintenance stages remains limited. D'Amico et al (2022) demonstrated the possibility of creating a digital twin model by combining geometric and design information with monitoring results obtained from road infrastructure. Bosurgi et al (2020) attempted to apply BIM in road maintenance management by incorporating survey data related to road conditions into the I-BIM model, resulting in a more efficient and simpler management system. However, it was a preliminary experimental approach, and the detected distresses were not visually presented to provide maintenance guidance. Therefore, this paper aims to enhance the efficiency of pavement maintenance management by visualizing pavement distress using BIM.

METHODOLOGY

The proposed framework integrates the concept of Lean to increase the efficiency and accuracy of pavement distress detection and management. The process consists of three parts and the framework is shown in Figure 1. The first step involves collecting point cloud data and preprocessing it to create a labeled dataset for network training. Second, a 3D object detection method-PointPillar(Lang et al, 2019) is applied to detect pavement distress. Finally, the results are integrated into a pavement BIM model by using Dynamo to establish families of pavement distresses and visually manage the detected distresses. By continuously improving the accuracy of distress detection and efficient visualization management, this method will drive the transformation towards a more intelligent and effective pavement maintenance system.

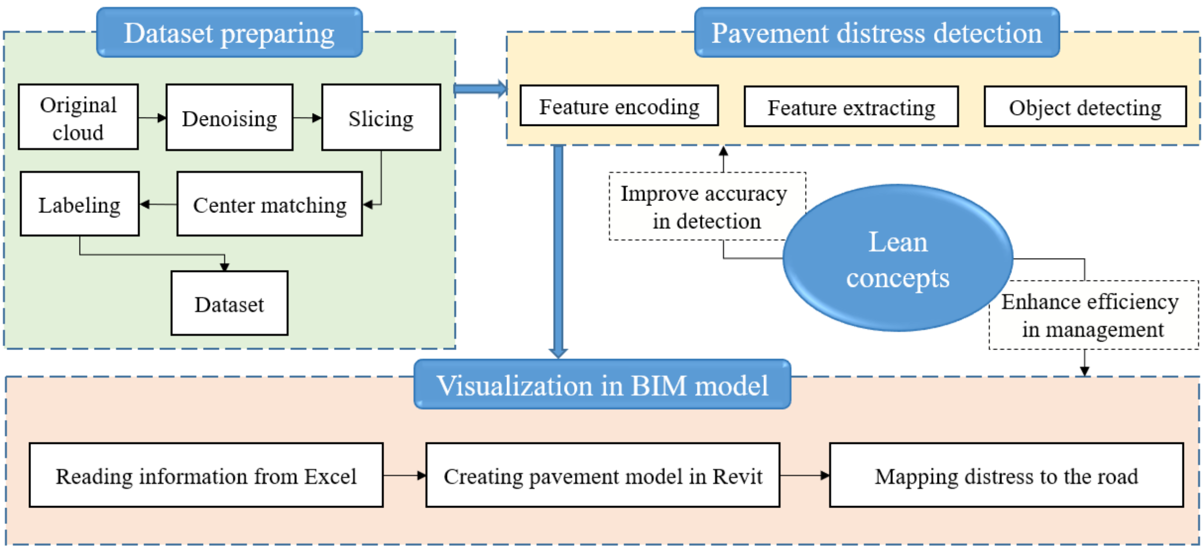

Figure 1: Workflow of pavement distress detection and visualization

ESTABLISHMENT OF PAVEMENT DISTRESS DATASET

This paper applies the vehicle-mounted LiDAR system to acquire pavement point cloud data and the types of pavement distress include transverse crack, longitudinal crack, alligator crack and pothole. Before sending point cloud data into neural network for training, the data needs to be preprocessed and annotated to create the dataset. The process of point cloud data processing is shown in Figure 2.

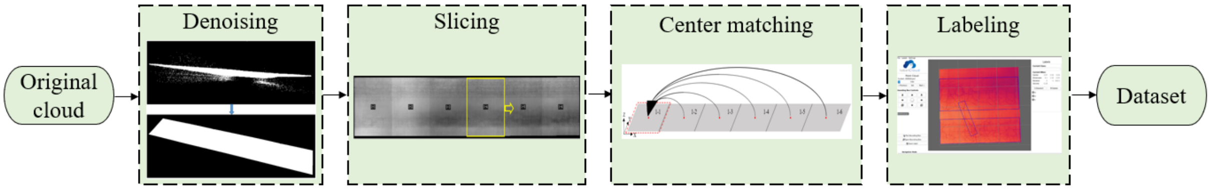

Figure 2: Data processing flow

The original point cloud data contains a large amount of noise and other less useful points, which can negatively affect the accuracy of detection results. To address this problem, this study combined two different methods to filter out the noise. The first method used is passthrough filtering, which is applied to eliminate the noise present in a wide range above the road surface. This method works by removing points that have values outside the given range in the specified dimension. After rough denoising, the statistical outlier removal (SOR) filter is used to remove noise more finely. The SOR filter calculates the average distance of each point to its K nearest neighbors. Assuming that the distance of all points in the point cloud data conforms to a Gaussian distribution, with its shape determined by the mean μ and standard deviation σ, the distance d from the nth point P_n (X_n, Y_n, Z_n) to any other point P_m (X_m, Y_m, Z_m) is calculated as follows:

$$d=\sqrt{(X_n - X_m)^2 + (Y_n - Y_m)^2 + (Z_n - Z_m)^2} \tag{1}$$

$$\mu=\frac{1}{n}\sum_{i=1}^{n} Si \tag{2}$$

$$\sigma=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Si - \mu)^2} \tag{3}$$

After denoising, the collected pavement point cloud data need to be divided into smaller one to adapt the training requirement of network model due to the limited computing resources. In this paper, in order to reduce the computational cost during model training, the full-scale point cloud is divided into many smaller size blocks by using a sliding window with size of 4×4 m^2. These smaller blocks are indexed to represent different sections of the road, and rough registration is necessary to ensure that the coordinate values of the point cloud blocks fall within the same range, which can provide more standardized data for neural network model training. Finally, the point cloud labelling tool is used to label the category and position of distresses with 3D bounding boxes and created the pavement distress dataset.

DEEP LEARNING-BASED PAVEMENT DISTRESS DETECTION

The aim of pavement distress detection is to classify and localize pavement distress automatically based on collected point cloud data, and provide specific information for pavement maintenance and management. The network architecture used in this study is called PointPillar(Lang et al, 2019) which offers a balance between speed and accuracy in 3D object detection algorithms. The implementation of PointPillar involves three main steps and the framework is shown in Figure 3.

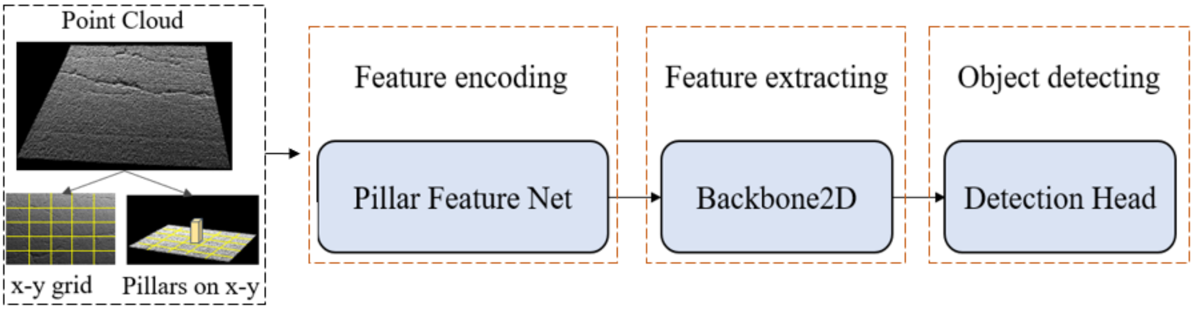

Figure 3: The detection framework of PointPillar

The first step is feature encoding. The point cloud is divided into a grid in the x-y plane and pillars are created with unlimited z extent. The points in each pillar are then represented as a 9D tensor. The input data is then sent through a linear convolution, transforming the 9D feature to 64D. Max-pooling is performed to create an output tensor of size (C, P). Finally, the encoded features are transformed into a pseudo-image by scattering them back to the original locations.

The second step is feature extracting. The backbone of PointPillar has two subnetworks: one is a top-down network that produced features with sufficiently small spatial resolution and this process can be represented by a series of blocks with Conv2D (C_{in}, C_{out}, k, s, p), where C_{in} and C_{out} are represented the input and output channels, k, s , and p are represented the kernel size ($k \times k$), stride size, and padding size respectively. The other one is a upsampled network with $Deconv2D$ (C_{in}, C_{out}, k, s, p), and each 2D convolutional layer followed by BatchNorm and ReLU sequentially. Finally, the upsampled features are concatenated to constitute high resolution feature map.

The third step is object detecting. After the feature map is extracted by the backbone network, the detection head is used to predict 3D bounding boxes of distress. The approach involves setting default boxes for each category, and each default box with two rotations and one scale which can roughly represent the dimension characteristics of different distresses. The default boxes are then matched with ground truth using 2D IoU and the shape offsets and confidence for all object categories are predicted. The height of the bounding box is not used for matching, but rather as an additional regression target.

BIM-based Pavement Distress Visualization and Management

After the distresses are detected by PointPillar, Dynamo is utilized to visualize the pavement and distress in BIM environment. This process simplifies the representation of the pavement in the realistic 3D environment, and specific routines have been coded for distress mapping to the pavement model, which can provide more intuitive information for road maintenance. To visually manage the detected distress in BIM environment, the pavement BIM model is created according to the collected point cloud data in this study. Then, the projected images of various distresses from point cloud are converted into maps by the method of generating ground, and their morphology and related parameter information can be shown in BIM environment. The procedure is shown as Figure 4.

This section mainly includes creating a node program by using Dynamo which is capable of reading data from Excel spreadsheet that contains the detected pavement distress information. Then according to the geometry and coordinate information of different distresses, the distribution scope of length and width on the pavement is calculated, and a number of points with corresponding X and Y coordinates can be generated based on the scope matrix. Finally, the pavement distresses were created in the BIM model for visual management.

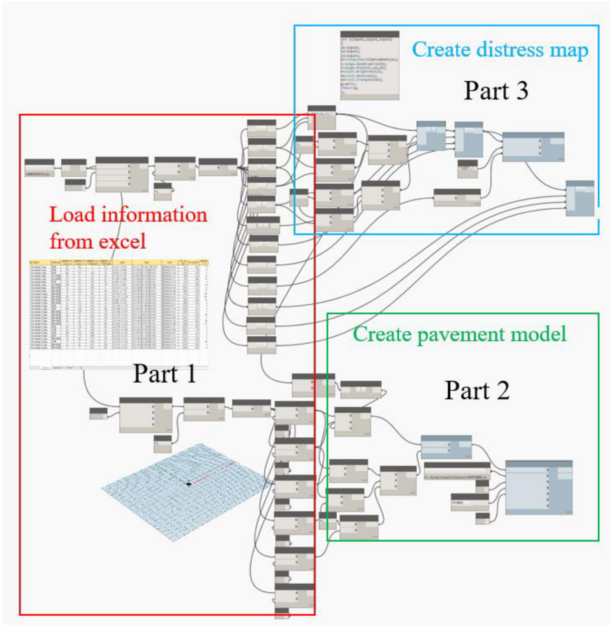

Figure 4: Visual programming to generate model in Dynamo

THE APPLICATION OF THE LEAN CONCEPT

The implementation of lean principles in the proposed method is based on the idea of continuous improvement. The solution uses a combination of advanced technologies, including deep learning and BIM, to streamline the pavement distress detection and visualization management process. By using the 3D object detection network PointPillar to automatically detect pavement distress, the solution reduces the time and effort required for manual inspections. Additionally, the use of BIM for visualization of the pavement and distress allows for a more efficient and effective management of the pavement, as the information is presented in a clear and intuitive manner.

The method also incorporates a proactive approach to maintenance, which is an important aspect of lean principles. By detecting pavement distress early and visualizing it in BIM, maintenance can be planned and executed more efficiently, reducing downtime and the potential for safety hazards. In addition, this study provides specific information about the pavement distress such as dimension and location, which can be used to inform maintenance and management decisions and continuously improve the process.

EXPERIMENTS AND RESULTS

To demonstrate the practicality of the proposed method, the prepared dataset is used for the model training, and then the trained model is used to detect the distress on a new complete road section. After obtaining the detected information of the distress, Dynamo is successfully applied to map the distress to the road model in BIM. And the detailed information of the distress can be viewed in the attribute column, which provide efficient and effective guidance for pavement maintenance.

THE EXPERIMENT SETTING

To carry out the experiment, high performance workstations are utilized with the following specifications: 4 NVIDIA GeForce RTX 3090 GPUs, 1 Intel Xeon Sliver 4210R CPU, and a Linux system to set up the training environment. The detected network PointPillar is initially designed mainly for use in the field of autonomous driving, and all experiments are based on the KITTI object detection benchmark dataset (Geiger et al, 2012) which consists of both lidar point clouds and images. Therefore, before model training, some details need to be adjusted to adapt the detection task of pavement distress. Firstly, the custom $Dataset$ need to be developed, and the most important step is to load prepared training data, then the annotated point cloud coordinate system must be adjusted to the Lidar coordinate system through a simple transformation, with X, Y, and Z being the inputs for the network and x, y, and z being the label coordinates and d being the height of the Lidar sensor.

THE RESULT OF PAVEMENT DISTRESS DETECTION

The trained model is utilized to detect the pavement distress and predict 3D bounding boxes for each object with a confidence score. Figure 5 shows the detection results and different colored 3D bounding boxes represent different distresses. Compared with the ground truth, the predicted result of the trained model has a good performance.

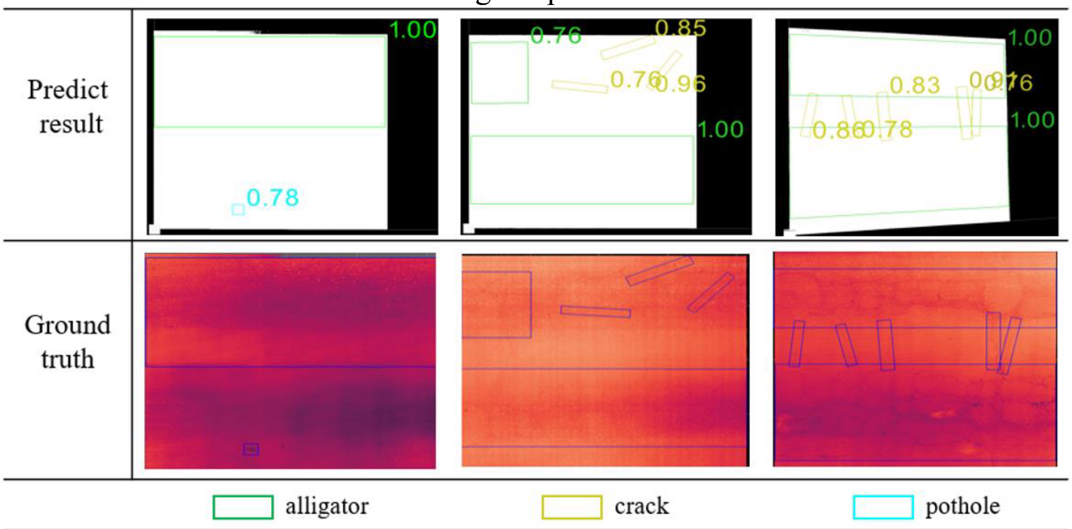

Figure 5: The comparison between predict result and ground truth

Then, the features of the distress including dimension and location information of the predicted 3D bounding boxes are extracted and stored in the spreadsheet. A portion of the collected information is shown in the following Table 1. The experimental results demonstrate that the 3D object detection algorithm based on point cloud data applied in the field of autonomous driving, as presented in this paper, has been successfully applied to automatic pavement distress detection, exhibiting both logical and functional correctness, and possessing certain practical value.

Table 1: Pavement Distress Information

Point cloud index	Class	Center coordinate X(mm)	Center coordinate Y(mm)	Rotation（rad)	…
1	Alligator crack	207	307	3.1408	…
2	Alligator crack	204	89	3.1323	…
. . .	. . .	. . .	. . .	. . .	…
26	Pothole	2191	139	4.1863	…
27	Transverse crack	2324	226	3.1565	…
28	Transverse crack	2449	204	3.1356	…

The Result of Pavement Distress Visualization

After preparing the information of pavement distress, Dynamo is used to read and import those data into Revit for modelling. As described in Section 3.3.3, the pavement model is established first and the detail information of the pavement is shown in the Table 2.

Table 2: Pavement parameters

Length(mm)	Width(mm)	Material	Original point
2480	392	asphalt	(0,0)

Finally, based on the coordinate and dimension information, all the distresses are created and mapped on the pavement with different colours representing different types. The parameters of each distress will be displayed in the attribute column and the visualization results are shown in Figure 6. After the successful modelling of pavement distresses, road managers can use the information query function of Revit to view the coordinates and dimensions quickly and analyze the distribution of the defects efficiently, and provide intuitive and reliable information for road maintenance.

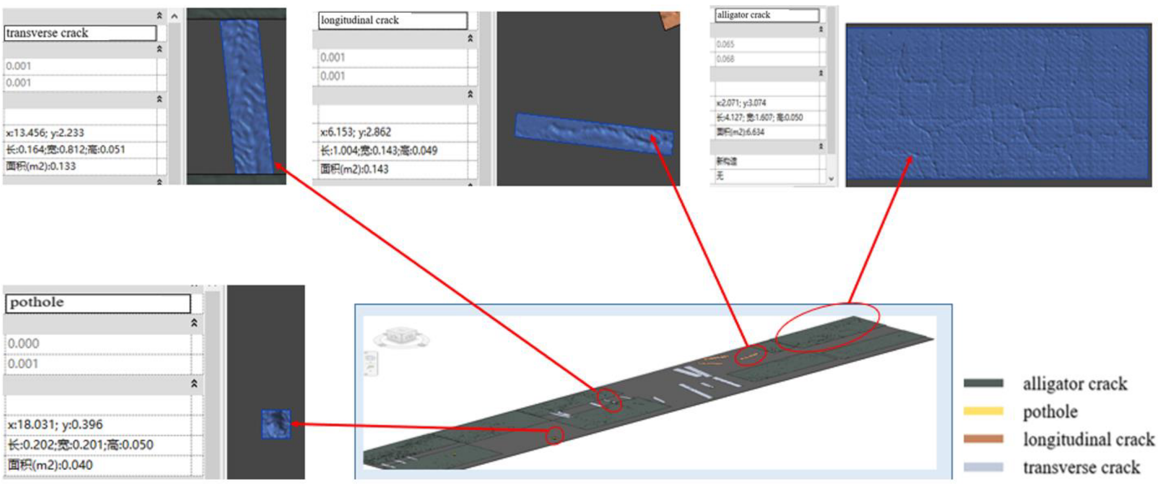

Figure 6: The visualization result of pavement distress

CONCLUSIONS AND FUTURE WORK

With the increasing total mileage of road maintenance management worldwide, traditional manual methods and two-dimensional inspection processes are no longer able to meet practical needs, and more efficient and reliable new technologies must be introduced. The advantage of 3D point cloud data makes it a potential method to improve the accuracy and reliability of road maintenance for detecting and quantifying the pavement distress. Therefore, a framework for automatic pavement distress detection and visualization management by using point cloud data, a deep learning-based 3D object detection algorithm, and BIM technology is proposed to improve the efficiency and effectiveness of pavement distress detection and visualization management.

Firstly, the collected point cloud data are pre-processed and a dataset of pavement distress is established. Then, the deep learning-based 3D object detection model PointPillar is applied to detect the distress automatically. After obtaining the detection information of the distress, Dynamo is utilized to realize the visualization of pavement distresses. In conclusion, the method utilizes advanced technologies to automate and streamline the process, while also incorporating a proactive approach to maintenance and a focus on continuous improvement.

However, in this study, the point cloud labelling process is manual and time-consuming which lead to a heavy workload. Therefore, a semi-automatic point cloud annotation method will be explored to reduce the burden of labelling. In addition, while the current 3D object detection method can achieve distress classification and localization, the extracted geometric features for severity assessment are region-level. To improve accuracy, point-level segmentation will be considered for more accurate distress quantification in the future.

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CONSTRUCTION PRODUCTIVITY GRAPH: A STRUCTURED FRAMEWORK TO ENHANCE PRODUCTIVITY AND SAFETY ON CONSTRUCTION SITES

Francesco Livio Rossini[1] and Gabriele Novembri[2]

ABSTRACT

The construction industry is characterised by the constant production of unique products in dynamic contexts where, moreover, the workplace coincides with the product itself. This limits the adoption of standardization and process automation methodologies. Furthermore, the average size of professional firms and companies often does not allow for investments in process innovation or skills development. Then, we need to consider that construction is a highly risky activity, also to the lack of standardization as aforementioned.

The paper aims to present the framework of a methodology based on linking the information managed by a BIM model with Agent-based simulation techniques - ABS. The scope is to simulate the duration of the work under efficient conditions, understood as the best occupation of the available areas by a suitable number of workers. The result is the Construction Productivity Graph - CPG, a graph that indicates the optimization level of the construction process.

KEYWORDS

Project construction management, agent-based modelling and Simulation, health & safety management, location based management – LBM, business process modeling – BPM.

INTRODUCTION

Nowadays, the situation of the construction industry sees an important recovery in demand against a significant increase in the cost of raw materials. This, combined with the difficulty in finding skilled labor, has led to a significant increase in costs, after decades of stagnation and recession in the construction sector.

This situation leads to a renewed interest in reducing the resources to be used in building processes, above all by aiming to reduce waste in terms of materials and time spent.

This research has the objective of saving resources by optimizing construction times, intervening through more efficient management of the work areas. At the same time, it is important to reduce interference, an important cause of injuries during construction works. So, the optimized management of the areas also brings a higher level of safety, given by the lack of overlapping of activities with different risks which, if overlapped, can cause accidents. Finally, especially in the early experimental stages, it was possible to verify how this type of approach also leads to an optimization of the supply chain, due to the possibility of managing the material

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storage areas in a better way and reducing wasted time due to inefficient material handling. (Amiri et al., 2017) and the reworking activities due to variations, which can also result from design errors (Scherer & Schapke, 2011). This issue is known in the building industry for decades, finding a whole series of answers in the application of lean methodologies. However, their diffusion is affected by the traditionally low interest of the construction industry towards technological innovation. Furthermore, it should be considered that these approaches still require investments which, in an economic context that sees companies fragmented in size that limit the possibility of investments, ends up always believing in consolidated procedures or, in the worst-case scenario, evaluating the inefficiency more cost-effective. Finally, it should be noted that a process supplied with optimization methodologies has a lower accident rate, due to the organizational level that lie beneath optimization techniques in general (Elghaish et al., 2019).

An important contribution to process optimization has been given by the growing diffusion of the BIM methodology. This allows the exchange of information through a single and shared model, on which a whole series of verification and analysis activities capable of increasing productivity and the reliability of results can be activated.

In the proposed framework, the BIM model is connected to an agent-based simulation model via API. Each component of the model is connected to an agent equipped with rules, objectives, and behaviors to achieve them. These aspects, typical of agents, allow the model to adapt to any changes in objective (design intent) and context (BIM environment). Furthermore, the agent can carry out self-test activities, and therefore dynamically verify the maintenance of any parameters set by the designer.

Once the characteristics of the project have been defined, the agent model activates a 'Master Actor' who, being hierarchically above the others, has the role of activating the agents who represent the working groups. These are related to the work to be carried out in the assigned work area (location) therefore the agent system defines the duration and the number of resources foreseen. The result is the representation of the Construction Productivity Graph - CPG, a synthesis of these computational processes aimed at explaining the location of tasks and the appointment of the number of workers per construction site area. The dynamism of this methodology is therefore useful not only in the design phase, but also during the execution and management of the construction site, since it is sensitive to variations, unforeseen events and changes of objective, through continuous and traceable updating of the project database (BIM model).

BACKGROUND

ABOUT ADVANCEMENT OF LEAN CONSTRUCTION

The lean methodology is based globally on the reduction of waste that can be generated along the course of a process. The objective is in optimizing of the chain of labor and the reduction of resources employed to parity of result, more and more current thing in consideration of the current scarcity of energy and raw materials (Carvajal-Arango et al., 2019).

From the point of view of building production, optimizing processes also means taking care of the quality of concrete production operations, with repercussions on safety and quality of working life in general. So (Schimanski et al., 2021) analyses that, in the construction industry, the most widely used lean techniques are Just In Time - JIT, Total Quality Management - TQM and Location Planning System - LPS. In addition, from the experience of the years of the pandemic there is a growing interest in Agile, thanks to the rapid introduction of the techniques of dematerialization of processes even in a very traditional and focused on the real site, such as construction sector is. The growing, spreading of BIM then led to the development of specific prototypes such as KanBIM (Gurevich & Sacks, 2014). The goal of KanBIM is to control the workflow and visualize processes parameters inside a BIM model, where their entities represent the information database of the whole system. However, by analyzing the comparative tests produced on these tools, we can see that the main issue is the link between the BIM entity and the production of the optimized process diagrams according to Lean logic (Babalola et al., 2019).

The advantages of these methodologies, considering the current level of development and definition, concern above all a better control of aspects such as space management, the effectiveness of the logistic chain and an improved responsibility of the technical figures involved in the working phases. From the point of view of the management of workforce, we can see - from the cognitive point of view - a possible drop in attention and operational responsibility on the part of workers, due to the repetitive and constant application of work patterns set by the system. This, combined with a lack of training, can lead to less reactivity and efficiency in case of exposure to unforeseen risky situations (Celik & Gul, 2021).

One of the most common causes of accidents on site is linked to the failure to manage interference, both from a spatial and temporal point of view. The construction site, unlike the industrial production line, is extremely dynamic and susceptible to having work crews interfering in the same area, but with different risks. Furthermore, consider how much the human factor can still influence the risk conditions in the building industry, another factor to be limited with the increase in automation in the building industry, a further reason for encouraging the introduction of industry 4.0 protocols to encourage continuous and constant connection between the forecast/simulation model and the reality of the construction site, with a view to the preventive reduction of overlapping situations. (Pregnolato et al., 2022). A desirable goal is therefore to find a meeting point between human awareness in the management of repetitive actions, and process optimization understood as the systematic adoption of techniques and methods that are easily repeatable by workers, and which can also be transferred to worksite machines that can gradually be inserted into the work site, even as physical support for workers (eg. Exoskeleton) or wearable technologies in general. (Aguirre-Jofré et al., 2021).

The limits of this approach are the cost of installation and management, which are too expensive for small works, and to be applied in socio-economic contexts not technologically developed. Another important limit is the broadband availability, essential to ensure this flow of information. In construction works located in historic contexts, where thick walls or underground areas are present, it is difficult to ensure a complete ICT accessibility. It will be necessary to start thinking about site data networks intended as networks to be installed in parallel to the electrical ones, for making each point reachable by digital devices, also for linking these detailed models as required by the Digital Twin approach.

Agent-Based Model Integration For Overcoming The Limits Of The State Of The Art

A possible limitation of the above simulation models lies in the low weight assigned to the management of the working areas and tasks carried out by the workers, and in general for the management of overlaps. These, in addition to slowing down the working process and therefore the general quality of it, cause inefficiencies for the management of the supply chain, due to a reduced optimization of the spaces and therefore of the temporary storage space of the site.

The goal of an agent system is to predict the emerging behavior of the model (Khodabandelu & Park, 2021). This model is composed of agents, rules, behavior understood as the actions that enable the agent to comply with the rules and goals (Grignard et al., 2022). Of course, agent modelling is not the only way to introduce productivity into the decision-making process, as there are a whole series of methodologies that serve the same purpose, moreover they have already tried and tested in the manufacturing sector and considered for the construction sector such as Discrete Event Simulation - DES and System Dynamics – SD (Lyneis & Ford, 2007). DES and SD follow a top-down approach, in which a system is built at the macro level at the beginning, then hypotheses are proposed, and its validity is measured, which is deeply based on empirical analysis, thus being affected by the implicit knowledge of the technician setting the model parameters (Fortino et al., 2005). Agent modelling follows the bottom-up approach, where the basis is the agents and the choices made to achieve their objectives in a heterogeneous or homogeneous/consequential manner, as is the case when pursuing swarm behavior (Zhang et al., 2019).

One of the fields in which the ABM approach is related to the solution of problems in the multi-options field, due to its ability to adapt the behaviors of the agents according to the different rules and objectives, according to the scenario. This dynamism makes the ABM simulation approach closer to the current building design and production, which is always determined by a constantly evolving context. In fact, while other simulation techniques tend to represent standardized actions in homogeneous contexts, the ABMS allows the modeling of the rules individually, and verifies the behavior of the agent both as a reaction of the individual to external stress, and through the verification of adaptation of the whole system with respect to external stimuli (Mathieu et al., 2018). However, ABM, following a bottom-up approach, can establish the interactive properties and characteristics of agents from the level of simple, reciprocal interactions, and thus produce an emergent result at the macro level. This characteristic makes ABM a preferable solution for the activation of what-if computational processes, without relying heavily on empirical analysis, excessive assumptions or directing the model in a preordained and biased direction (Khodabandelu & Park, 2021).

In conclusion, thanks to the ABM, the management of interferences for safety purposes can be much more accurate since it is effectively linked to dynamic changes in the context, and useful for the continuity checks that must be carried out to verify that the site is compliant with the H&S rules. At the same time, it is possible to increase the reliability of the forecast of the spaces occupied for the storage of materials and the installation of components, with related advantages over the management of the supply chain.

METHODOLOGY

The aim of the research is to set up a methodology potentially able to reduce the uncertainties in building production, above all when given by the lack of knowledge of the positioning of the personnel and of the equipment used. The result is a constant check, conducted by the agent system on the data flow provided by the BIM model, with respect to compliance with the needs of productivity and compliance with safety. Then, it is possible to further improve the synergies between the detailed progress of the works and the evaluation of the interferences of risk prevention. From this point of view, the first phase of the work consists of an accurate modeling of the site and the building, for having a reliable match between the reality and the digital model. (Abune'meh et al., 2016). Therefore, the first phase analyzed concerns the expected modeling specifications, where the level of detail of the BIM elements must follow the overall needs, assuming for the identified purpose an always very high level, bordering on the needs related to facility management. These elements are then managed by a Work Breakdown Structure - WBS, capable of linking the properties of the element with the workings connected to it. Following consolidated workflows, the federated model (i.e. The model includes the various WBSs for the different technical domains), is subjected to clash detections, aimed to filter critical issues in the project right from the start. The positive contribution that the implicit (i.e. Subjective) knowledge of the human designer can give, which includes his evaluations, is not overlooked. These are useful both for the purposes of improving the project being defined, and for training a possible machine learning engine towards more suitable solutions in similar future cases. (Figure 1). Once a BIM model suitable for construction analysis has been got, agent-based simulations can be activated, which will define the number of workers required to perform the planned activities in the respective locations (Antwi-Afari et al., 2018). The location is the functional unit of the construction site, a set of locations encompassing homogeneous work where resources can be allocated. Once the work to be carried out in the locations has been organized, the system automatically starts the verification of the propaedeutic and proximity to the horizontal and vertical communication ways of the construction site, for reducing wasted time and interference that may arise from the mere transit of materials through the site.

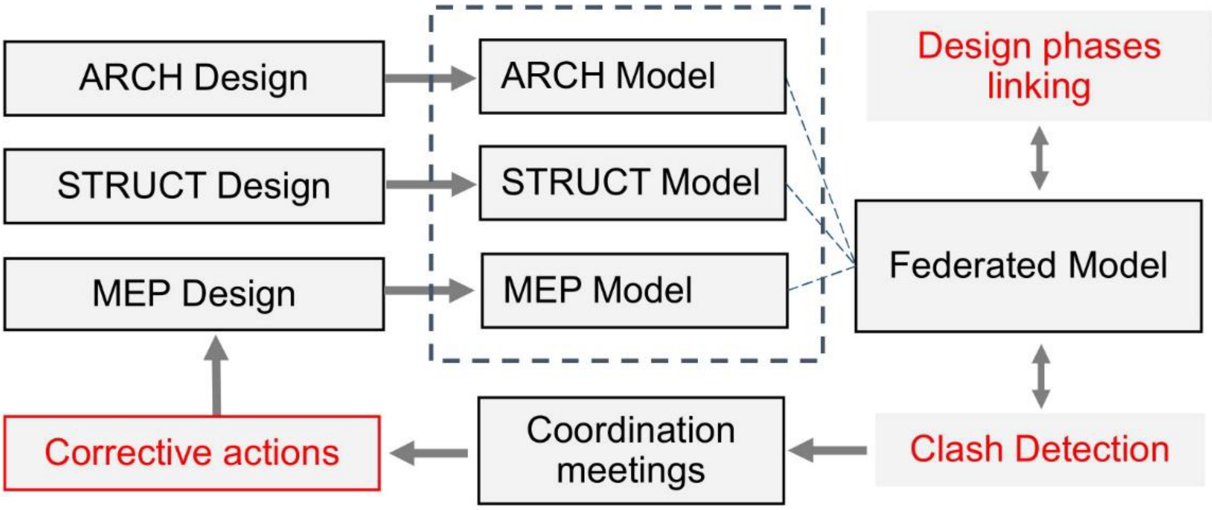

Figure 1: summary of the BIM model checking process.

BIM MODEL VALDATION THROUG MICROSERVICES

This paper describes the methodological approach for a future case study to be applied to a real construction site. The first step consists in importing a BIM model with a minimum LOD of 400, for having a sufficient level of information due to a consistent checking phase, and at the same time enough information to feed the proposed simulation system, or other linked machine learning based tools.

To manage this huge amount of information, often coming from different actors and, above all, subject to numerous updates and alignments during the phases from design to construction, the two approaches of the BPMS protocol can be taken into consideration. The first concerns a centralized orchestrator, where there are a whole series of microservices that gravitate around a centralized management system. The second instead appears as a choreography of microservices where, in a circular and one-way direction, there is a continuous exchange of information where the previous actor updates/modifies the information and sometimes the actions of the predecessor.

The result of the comparison showed that, in this specific case, it was preferable to set up a centralized microservice orchestrator for a matter of scalability of the system and identification of the contribution of the single microservice (Figure 2).

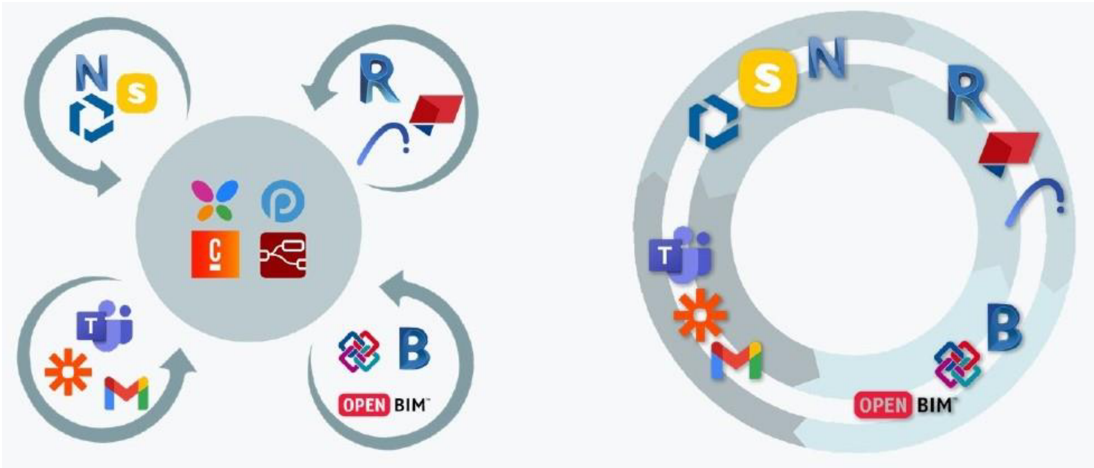

Figure 2: On the Left, the Conceptual Schema of a Centralized Orchestrator; on the Right the Choreography One.

AGENT MODELING FOR THE ASSIGNMENT OF LOCATION AND CREWS

Orchestration using microservices allows you to conduct a whole series of updates, variations, and checks without risking major project inconsistencies. Of particular importance will be the verification of correspondence between BIM elements, possibly updated with respect to all the checks carried out, and the connected work activities, according to the WBS approach.

The analysis of the workings is of particular importance for the subsequent modelling phase of the agents, since they will have to adapt their behavior with respect to the specific rules of the workings, both in terms of productivity and in terms of safety.

Once the modeling of the rules and behavior of the agents has been completed, their activation will be delegated to a Master Actor who, according to the logic of the actors, manages the workflows by activating or not the agents, according to the breakdown into phases envisaged by the WBS. Therefore, we model the WBS themselves as Agencies, i.e. Systems that contain within them other agents that represent simple components and elements. The most important rules regarding the location of the intervention, the productivity of each working team and the need for operating space, and the respect of priorities or the sequence in general of the work activity analysis. The establishment of these rules is decisive for managing the optimization of times and resources, given that a large part of the optimization conditions derives from the possibility of using multiple locations, managing interferences and the possibility of using shared logistic conditions to reduce the areas transit and handling of loads on site, conditions characterized by a high risk of accidents. This activity also helps to correctly evaluate the lost time of transport within the site. The result is the production of a table that summarizes the number of resources to be employed, the location to occupy and the duration of the work. (Figure 3).

Starting Date		1	2		2	3		3	4	
17/11/2022 8.00	Location 1 (2h)	Location 1 Start	Location 1 Finish	Location 2 (2h)	Location 2 Start	Location 2 Finish	Location 3 (2h)	Location 3 Start	Location 3 Finish	Location 4 (2h)
Task 1	32	17/11/22 8.00	21/11/22 13.20	32	21/11/22 13.20	24/11/22 10.40	32	24/11/22 10.40	29/11/22 8.00	32
Task 2	38	16/12/22 10.40	19/12/22 15.20	38	19/12/22 15.20	21/12/22 12.00	38	21/12/22 12.00	23/12/22 8.40	38
Task 3	105	3/1/23 16.00	6/1/23 13.00	105	6/1/23 13.00	11/1/23 10.00	105	11/1/23 10.00	13/1/23 15.00	105
Task 4	25	16/1/23 8.00	18/1/23 8.40	25	18/1/23 8.40	20/1/23 9.20	25	20/1/23 9.20	24/1/23 10.00	25
Task 5	50	7/2/23 13.20	10/2/23 14.20	50	10/2/23 14.20	15/2/23 15.20	50	15/2/23 15.20	21/2/23 8.20	50
Task 6	72	23/2/23 8.00	27/2/23 8.00	72	27/2/23 8.00	1/3/23 8.00	72	1/3/23 8.00	3/3/23 8.00	72
Teams Name	Members									
Team 1	3	17/11/22 8.00	21/11/22 13.20	24/11/22 10.40	29/11/22 8.00	1/12/22 13.20	6/12/22 10.40	9/12/22 8.00	13/12/22 13.20	16/12/22 10.40
Team 2	6	16/12/22 10.40	19/12/22 15.20	21/12/22 12.00	23/12/22 8.40	26/12/22 13.20	28/12/22 10.00	29/12/22 14.40	2/1/23 11.20	3/1/23 16.00
Team 3	10	3/1/23 16.00	6/1/23 13.00	11/1/23 10.00	13/1/23 15.00	18/1/23 12.00	23/1/23 9.00	25/1/23 14.00	30/1/23 11.00	2/2/23 8.00
Team 4	3	16/1/23 8.00	18/1/23 8.40	20/1/23 9.20	24/1/23 10.00	26/1/23 10.40	30/1/23 11.20	1/2/23 12.00	3/2/23 12.40	7/2/23 13.20
Team 5	4	7/2/23 13.20	10/2/23 14.20	15/2/23 15.20	21/2/23 8.20	24/2/23 9.20	1/3/23 10.20	6/3/23 11.20	9/3/23 12.20	14/3/23 13.20
Team 6	9	23/2/23 8.00	27/2/23 8.00	1/3/23 8.00	3/3/23 8.00	7/3/23 8.00	9/3/23 8.00	13/3/23 8.00	15/3/23 8.00	17/3/23 8.00

Figure 3: The Output of the Agent-based Simulation, Indicating Tasks, Locations and Time Needed.

Once the number of workers has been got from the agent system in relation to the work to be carried out for each location, a new micro-service is activated, aimed at the graphic visualization and verification of interference in relation to the activities expected for each location and the number of workers used. Simple spreadsheets on accessible and widespread formats such as *.xlsx were used to define these graphs. From there, the Location Based Structure is set up, so that the duration of work, the maintenance of the optimal workflow average and any overlaps can be fully visualized.

After an initial series of inferences, the agent system establishes a balance between the number of workers, the duration of the activities and the occupation of the areas. Once this information has been defined, graphically represented according to the standards of the Location Based Structure, in order to verify, also graphically, the existence of overlaps or interferences, as well as the possibility of having the expected number of workers.

To define these graphs and make them as interoperable and accessible to as wide an audience as possible, simple spreadsheets in *.xlsx format were used.

The first result shows the expected number of people, the duration of the work and the teams involved (Figure 4), according to simple straight and oblique lines. This type of scheme is unique for each location, and in any case already guarantees, at a local level, initial checks on compliance with the maximum number of people allowed on site, on the equipment and on the possibility of managing areas for the storage of materials. Once the congruence of the works inserted in the individual areas has been verified, we can enter the result relating to the entire construction site into the system, to have a complete view of the optimized consecutiveness of the works.

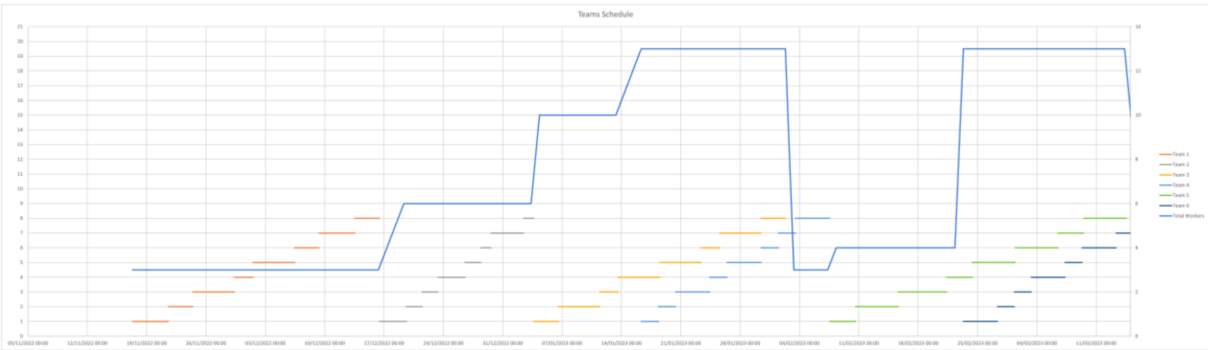

Figure 4: CPG Sample: in Blue the Number of Workers; the Horizontal Lines Describe the Duration of Tasks and the Team Involved. Analysis Conducted for a Single Location.

A further step is the one-to-one link between these results and the BIM model, especially if it is not possible to proceed with the forecasts resulting from the simulation phases.

The objective, through the APIs of the BIM editors used, is to update the simulations on the basis of the information contained in the objects and also the opposite, so as to make the simulation model not only a tool for verifying and organizing the phases of processing, but also a design support, in the sense in which the BIM object can be adapted to the production and safety needs of the construction site..

DISCUSSION

In a first development of this framework, we can observe an underestimation of the productivity reduction factor due to peak occupancy, and an overcrowding in certain areas that are also at high risk, such as in the hypothesis as shown in (fig. 05). Further improvements of this study will keep in analysis, real construction sites and their development compared to forecasting.

We can overcome this type of weakness could through the improvement of the predictive model techniques based on Bayesian statistics. So, in this way will be possible to enhance the correctness of a forecast produced by Bayesian analysis of previous similar cases. These forecasts will be based on expert judgement and the combination with the context. Finally, the future works need to overcome those issues:

- Scalability of the system: considering the large amount of detail required for BIM and agent modelling, there are major limitations regarding the machine's ability to process such large data volumes in a relatively short time. It could be interesting to evaluate the development of digital meta-models, in which will be show representative values of the project, to carry out rapid assessment, creating a new design level named ‘constructive feasibility’.
- Forecast accuracy: to have an adequately accurate forecast model, it is necessary to feed the database of similar events with a good amount of data, as is for the ‘big data’ approach. This consideration may find many practical obstacles, since the construction plans of construction sites, execution methods and metrics of executed projects are sensitive information, proportional to the intended use of the building itself, and therefore problematic to publish. Likewise, it is difficult to create a common data sharing environment from the point of view of the production process of construction companies, which have part of their capitalization and value in the construction and maintenance of best practices and standardized procedures. So, it would be interesting to consider a free digital platform of references in this sense, produced by public institutions that, depending on the type of intervention carried out and the sensitivity of the building, could make available on an open platform with all information necessary to train data libraries dedicated to the construction elements of the building, and to the related agents and rules.
- Auto-generative knowledge: it would also be interesting to gather the experiences gained on the building site itself, and to consider these as a basis to improve the decision-making process for the following construction phases.

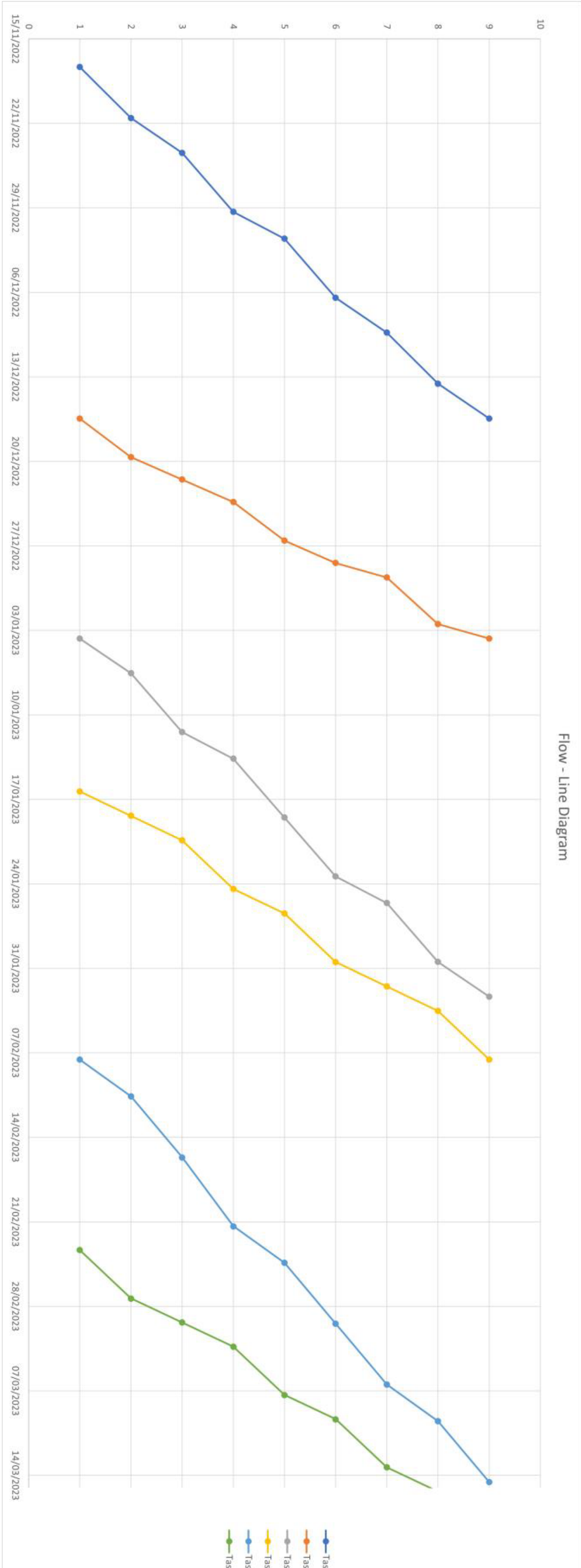

Figure 5: An Overview of the Line of Balance of the Site.

CONCLUSIONS

The proposed methodology takes as its reference the best practices related to lean construction applications, from which derives the conceptualization of CPG. In this management process, the BIM model is the accurate database from which to take and input data following the processing of the ABM simulation results. This information flow, guaranteed by the service orchestrator and managed via APIs, opens interesting perspectives from the point of view of the method's subsequent evolutions. Thus, other micro-services could be added to the workflow, to make the results increasingly accurate, but accepting a reduction in the modelling and simulation execution speed. From the point of view of 4.0 implementation, trusting also in the possibility of having an adequate ICT infrastructure, the possibilities of using wearable technologies connected to the simulation environment could be implemented. This could bring two results. The first one consists of an immediate communication between the system and the worker, who could be warned constantly about the activities to be carried out in the predetermined workplace; the latter instead concerns a continuous collection of data, to create an extensive database for subsequent machine learning applications.

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USING LOW-CODE AND ARTIFICIAL INTELLIGENCE TO SUPPORT CONTINUOUS IMPROVEMENT IN THE CONSTRUCTION INDUSTRY

Eder Martinez[1] and Diego Cisterna[2]

ABSTRACT

Low-code is a new technology paradigm used to support digitalization in different industries. Nevertheless, there are no studies analyzing the implications of this technology in the construction industry context. Through action research, this paper explores the potential of low-code to support continuous improvement of construction processes. The authors present the development and implementation of a low-code/artificial intelligence (AI)-based solution to automate data processing from paper delivery notes on-site. The as-is process was measured and compared against the low-code/AI powered process to verify efficiency gains. The development process of the digital solution was also analyzed to derive the findings of the study. The implementation of the digital solution resulted in 78% process time savings. The study also reveals the importance of involving people closer to operations in the development process, which resulted in efficient elicitation of requirements and the delivery of a solution meeting the needs of the end users. This paper highlights the potential of low-code productive development practices to support the digitalization in the construction industry. It also enlightens areas for further research and encourages the development of additional case studies to provide evidence of the benefits and limitations of using low-code to support continuous improvement in the construction industry.

KEYWORDS

Low-code, no-code, artificial intelligence, lean construction, continuous improvement

INTRODUCTION

Digitalization and the adoption of construction 4.0 offers the Architecture Engineering and Construction (AEC) industry a great opportunity to improve processes and productivity (Chui & Mischke, 2019). However, the architecture, engineering, and construction (AEC) sector lags behind other industries in terms of digitalization. According to the MGI Industry Digitization Index from 2015, construction was ranked third-to-last, ahead only of agriculture and hunting (Agarwal et al., 2016).

This slow pace of digitalization is usually attributable to systematic industry barriers such as fragmentation, organizational decentralization, and the uniqueness and transience nature of construction projects (Dubois & Gadde, 2002; Hall et al., 2020). In addition to these barriers, it

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is widely agreed that the main obstacles to digitalization in construction are not mainly technology-related challenges, but rather insufficient understanding of construction operations (Fenves 1996; Koskela & Kazi, 2003) and the socio-technical environment, which encompasses cultural and human factors relevant to digitalization (Lundberg et al., 2022; Xue et al., 2012) . This lack of understanding translates into a critical disconnection between the requirements of the industry and the way in which technologies are developed and implemented (Arayici et al., 2006).

Xue et al. (2012) acknowledge that despite the efforts put on the development of information technology to improve project performance, practitioners still face several difficulties when bringing it into real-life management and operational processes. It is therefore reasonable to assume that bringing the process of technology development closer to construction operations is particularly relevant to support digitalization and productivity improvement in the construction industry. Bridging technology and operations increases end-user participation in the development process, facilitates the elicitation of requirements and the validation of potential solutions, which in turn helps to ensure that the final solution meets end-user requirements.

An emerging technology paradigm offering opportunities in this area is low-code development (Richardson & Rymer, 2014). Low-code development allows individuals with limited coding skills to develop and implement digital solutions targeted to specific business needs. The potential of low-code lies in its capacity to allow people closer to operations (practitioners or end-users) to find digital solutions to their business challenges. Some authors refer to these individuals as “citizen developers” (Everhard, 2019; Olariu et al. 2016).

Bringing the technology development process closer to operations also aligns with Lean Principles. According to Liker & Meier (2013), from a lean perspective technology has to fit people and the processes they use in order to maximize its value. Furthermore, prior to digitalizing construction processes, it is necessary to assure their stability. Otherwise, digitalization could exacerbate existing problems and introduce new barriers. Stable processes complemented with suitable technology provide an opportunity for developing agile and more efficient information flows (McHugh et al. 2022).

Market and scientific literature forecast that low-code and citizen developers will play a fundamental role in enabling the digitalization of different industries (Prinz et al., 2021). Low-code has been already explored to improve processes in different business scenarios, such as manufacturing and supply chain management. Nevertheless, to the best of the authors knowledge there is no research contextualizing the use of low-code to support digitalization in the construction industry. This paper aims to fill this gap by providing insights about the use of low-code and AI to address challenges in construction processes.

RELATED LITERATURE

LOW-CODE

Low-code is a relatively new development paradigm. The term low-code was introduced by Richardson & Rymer (2014) who argue that it emerged in response to rapidly changing business environments and demands for faster and cheaper software development. Low-code development platforms support fast development of customer-facing applications, requiring minimal hand-coding and enabling productive development practices.

In practical terms, low-code lowers the barriers between software/application requirements and delivery, speeding up the development process and enabling higher customer participation in projects (Richardson & Rymer, 2014). Low-code platform users (citizen developers) use an application modeler with an intuitive graphical interface offering different predefined constructs assisting in the application development process. The user drags and drops different pre-defined constructs in the graphical interface which automatically generate the code in the background based on the choices made by the user. In this way, a user without advanced coding/programming skills can design and deliver fully functional applications or digital solutions without necessarily requiring the support of professional software developers (Sahay et al., 2020).

Some authors, however, argue that more than a disrupting technology, low-code can be considered as the evolution of model-driven engineering and Computer-Aided Software Engineering (CASE) concepts. Some authors even claim that the rise in low-code popularity can be attributable mainly to a rebranding and marketing of its predecessor concepts (Bock & Frank, 2021; Cabot 2020).

Aside from the debate about its roots, low-code ability to enable fast delivery of digital solutions is generating a significant momentum. Forecasts suggest that by 2024, 65% of business applications will be created using some form of low-code technology (Vincent et al., 2019), and the number of citizen developers will eventually surpass that of professional developers (Wong et al., 2019). If these predictions materialize, low-code technology will significantly influence digitalization in different industries and the way in which business processes are designed and run. In fact, the Project Management Institute (PMI) has launched an educational program to prepare the next generation of citizen developers (PMI, 2021). Scientific interest on low-code is also rising (Prinz et al., 2021), with some research projects focusing entirely on preparing future engineers make low-code scalable (e.g., Tisi et al., 2019).

Low-code has already been explored in different industries. Waszkowski (2019), used a low-code platform for automating business processes. The author emphasized that one of the primary advantages of low-code lies in its ability to significantly reduce the time required to transfer requirements from end users to information technology developers. Wolff (2019), described various examples of low-code implementation for digitalizing workflows services and inventory management. The author argued that low-code is especially suitable for manufacturing, given that most engineers who oversee business processes are acquainted with a programming language making the low-code environment relatively familiar to them. Sanchis et al. (2020) assessed the feasibility of using low-code to facilitate digitalization in the manufacturing sector. The authors emphasized that low-code interfaces with Internet of Things (IoT) and Industry 4.0 can greatly simplify the transfer of information and optimize equipment and products across the entire value chain. Wang et al. (2022) used low-code to develop a small-scale Enterprise Resource Planning (ERP) system tailored to the requirements of the context of hydrogen equipment manufacturing. The authors reported the advantages of the low-code-based ERP system compared to the prior semi-manual Microsoft Excel method. They also emphasized the potential of low-code to facilitate innovation and enhance business agility within an organization.

The authors could not identify any documented implementation low-code in the context of construction industry. That is one of the primary contributions to literature of this study.

USE OF AI IN CONSTRUCTION TO EXTRACT INFORMATION FROM DOCUMENTS

Low-code technology is evolving rapidly, and vendors are competing to offer the most intuitive and faster development environment (Vincent et al., 2019). Some vendors are even integrating AI modules into their platforms allowing users to create models to automate tasks such as paper form processing and object detection.

AI-enabled document processing can help reduce the time it takes to manually extract data from documents, while also reducing errors. AI-based document processing is used to scan and interpret documents, extracting the key data points that are needed for further analysis. (Cisterna, Seibel, et al., 2022)

Optical Character Recognition (OCR) and Natural Language Processing (NLP) are two AI technologies that could have a substantial impact in the construction sector (Locatelli et al., 2021; Wolber et al. 2021). OCR technology enables the conversion of scanned or digital images into text that is machine-readable, enabling the automation of human data entry and the digitalization of paper-based operations (Hamad & Kaya, 2016). NLP enables computers to comprehend and analyse human language, enabling them to interpret and process information from unstructured text data. (Indurkhya & Damerau, 2010)

One example of the use of OCR in the construction industry is in the digitalization of contracts and invoices. By utilizing OCR, companies can automatically extract information from these documents and incorporate it into their digital systems, thereby decreasing the need for manual data entry and enhancing accuracy and productivity. This also enables for improved tracking and management of crucial data, such as payment schedules and project deadlines.

NLP can be utilized in numerous ways to enhance construction operations. For example, it can be used to evaluate construction project reports and extract vital information such as status updates, budgets, and resource use. This data can then be used to track project performance and detect possible issues early on, enabling speedier resolution and improved project outcomes. NLP can also be used to automate communication amongst team members, such as informing project managers of potential delays or providing deadline reminders.

Another scenario is the application of NLP to the evaluation of construction site safety reports. By examining these records, construction organizations can find trends and patterns associated with safety events and utilize this data to improve safety processes and reduce the likelihood of accidents.

In conclusion, the employment of OCR and NLP in the construction sector represents a huge opportunity to enhance process efficiency and productivity. These technologies have the potential to make construction projects more streamlined, cost-effective, and secure by automating human operations and extracting important information from data.

RESEARCH METHODOLOGY

The authors used action research. Action research supports addressing practical problem-solving while expanding scientific knowledge based on collaboration of different actors within a mutually accepted ethical framework. The characteristics of action research offer an adequate framework for conducting applied research in the construction industry and foster collaboration between academia and industry practitioners (Azhar et al., 2010).

The authors collaborated with a construction project team in the implementation of a low-code/AI digital solution to address inefficiencies in the process of collecting and processing data contained in paper forms. The authors supported the team in the development process of the digital solution. The as-is process was mapped, timed, and ultimately contrasted with the improved low-code/AI-enabled process to identify the efficiencies that could be achieved through the implementation of the technology. Insights from the site project manager were captured through semi-structured interviews to support the findings of the study.

PROJECT BACKGROUND

The project involves the construction of a large tunnel in Switzerland. The operational challenges are related to a typical situation of manual data processing on construction sites. This process is depicted in Figure 1. For each concrete delivery truck, the construction team receives the corresponding delivery note onsite. Relevant information in the document (e.g., receipt number, type of material, date, quantity, etc.) is manually transferred to a spreadsheet to keep track of materials delivered on-site. The information is then processed to create a dashboard to visualize the information.

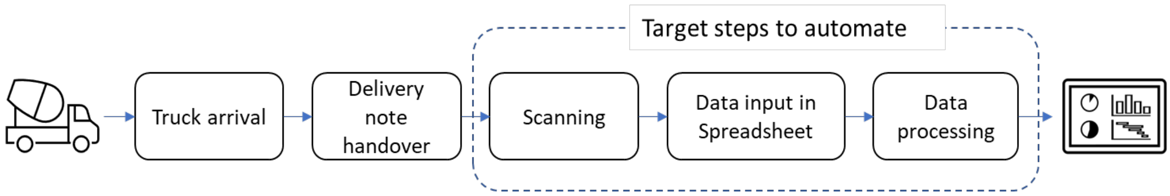

Figure 1: "As-is" Process to Collect and Process Data from Delivery Notes.

This process has several drawbacks. First, the manual transfer of information from the receipt to the spreadsheet is time consuming and prone to errors. People devote daily time to perform this task instead of focusing to deliver value to the project. Second, in many cases the responsible person does not perform the task on a regular basis. This generates a backlog of delivery notes which are not processed baring the project team to have accurate and timely information about the quantity of material received onsite. Although not considered in the scope of the process improvement, the delay in information processing also impacts downstream work. Since there is not an overview of the material received, the finance team is unable to centrally process invoices delaying the payment suppliers. The team aimed to address some of the inefficiencies in the process by leveraging the use of the low-code Microsoft Power Platform. Microsoft Power Platform includes a group of cloud-based applications supporting the automation of business processes and the creation of applications using low-code (Microsoft, 2022). The platform has also available an AI module which support training models to extract information from documents and images.

ARCHITECTURE OF THE SYSTEM AND UPDATED PROCESS

The architecture of the system is depicted in Figure 2. The digital solution leverages the use of the Microsoft AI builder, Power Automate, SharePoint, Excel, and Power BI. In the updated process, the user scans the delivery note and save it in a designated folder in Microsoft SharePoint. This action triggers a digital workflow in Power Automate which recalls an AI model created in Microsoft AI builder. This model is trained to read and extract relevant information from delivery notes. Power Automate then creates a new row with this data in a Microsoft Excel table. In parallel, the workflow triggers an automated confirmation email to the user including relevant information extracted from the document, including the scanned file as attachment for internal archive. Via an automated query, Power BI imports the table, organized the data, and display it based on visuals defined by the team.

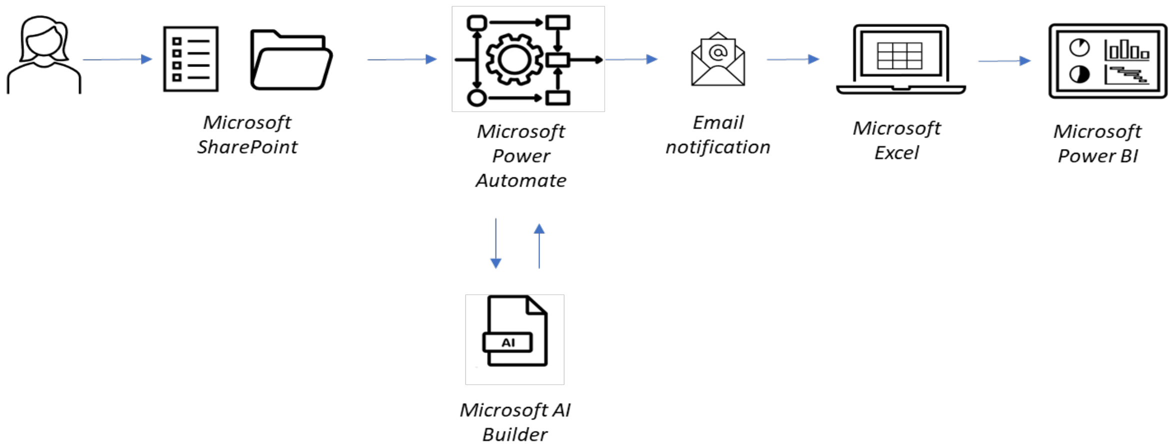

Figure 2: System Architecture.

The first step to develop the solution required training of an AI model able to extract relevant information from scanned delivery notes in .pdf format. For this purpose, the model was trained using 10 standard samples from a specific supplier. This step requires the user indicating manually the areas of the delivery notes where relevant data is located. In our case, we piloted the model using the name of the supplier, receipt number, date of delivery, the type of material delivered and corresponding quantity. After the first rounds with the sample delivery notes, the model provided an indication of the confidence for the different field (Figure 3). The model can be further trained to increase confidence requiring more samples to improve the AI model.

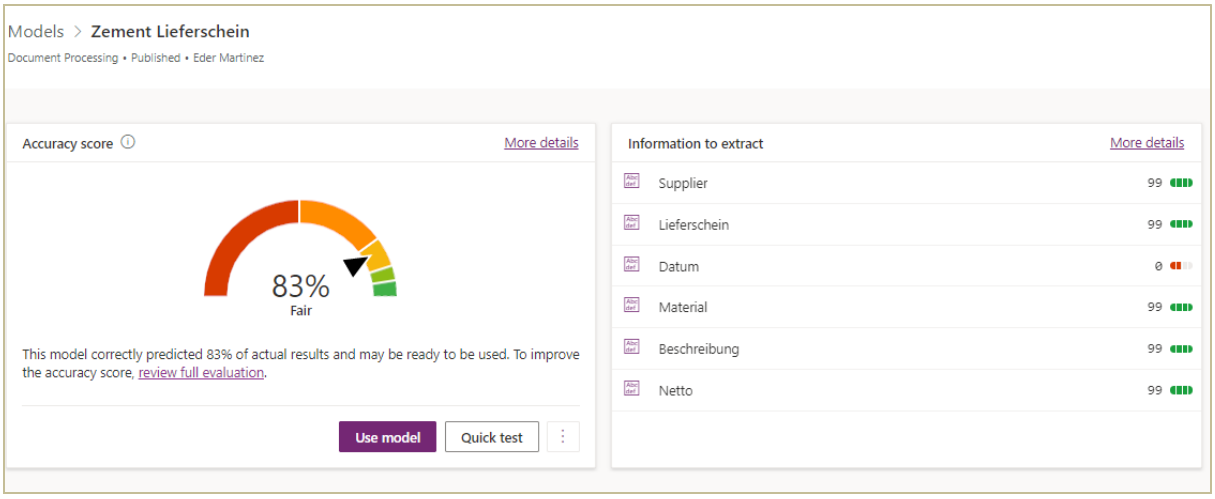

Figure 3: AI Model Accuracy Score.

DIGITALIZED VERSUS TRADITIONAL PROCESS

The new low-code/AI workflow removes several inefficiencies from the original process since the user no longer has to manually type the information in the spreadsheet. On average, the whole process took the user 7 minutes per delivery note. In contrast, the automated workflow takes on average 1.5 minutes, meaning that 5.5 minutes are saved each time the process runs, equivalent to 78% of the original process time.

The digital workflow in Power Automate itself takes in average 25 seconds, varying depending on the quality of the connection onsite and the amount of data in the paper form. For this calculation, we run the workflow 10 times and computed the average. An example of Power Automate workflow timing is depicted in Figure 4.

Furthermore, the digital process discourages producing a backlog of unprocessed delivery notes. Capturing of data, as well as the transformation process required to make information available is triggered as soon as the scanned file is stored in the designated folder. The solution also supports processes downstream since the information is directly made available to the finance department to process related payments.

The time savings may appear marginal when analysing a single process run. Nevertheless, efficiency gains can be scaled up and computed considering the magnitude of the project. It is expected that this project will receive more than 2,000 delivery notes only for this type of material and supplier. This translates into 183 working hours saved for the project. This does not consider other type of delivery notes (materials, equipment, etc.) or potential re-use of the low-code/AI solution in other projects within the organization.

The development process to put this solution together took approximately 1.5 working hours. That includes training the AI model (considering 10 delivery notes) and designing the workflow in Power Automate. This considers a user already familiarized with the Microsoft Power

Platform. For different type of delivery notes (e.g., different layout or supplier), the AI model should be re-trained, but the digital workflow logic could be reused.

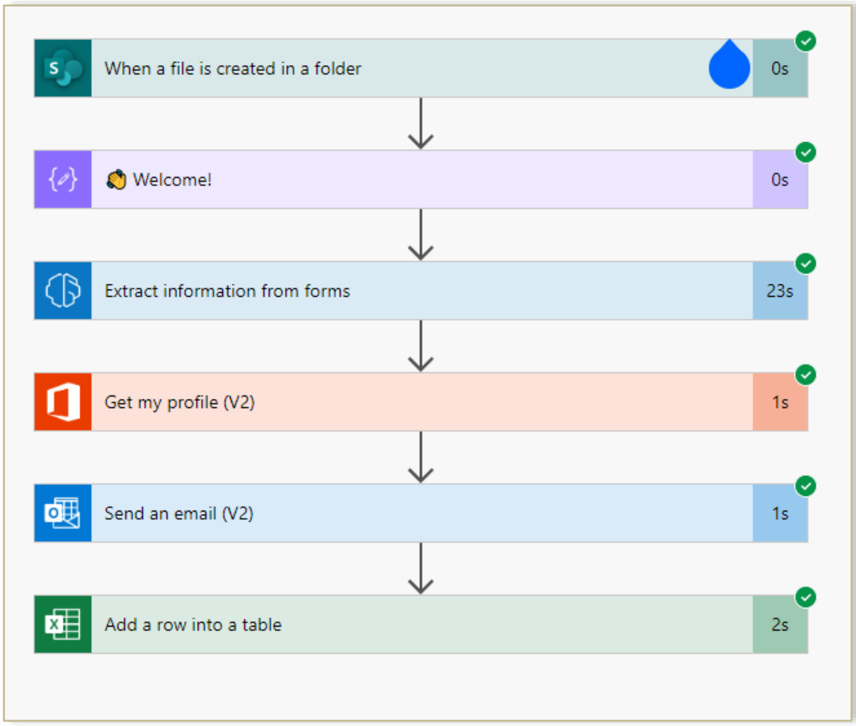

Figure 4: Power Automate Workflow and Duration.

DISCUSSION

THE POTENTIAL OF LOW-CODE IN THE CONSTRUCTION INDUSTRY

This experience demonstrates the potential of low-code and AI to support the digitalization of specific processes in the construction sites. The unique nature of construction results in a variety of specialized processes and procedures, making it challenging to find a ready-made digital solution in the market for those particular cases. Developing a digital solution in the traditional way would arguably require the involvement of information technology experts to support in the development process, which may result costly and time consuming.

With the availability of low-code and AI solutions, people closer to construction operations (acting as citizen developers) can experiment to develop their own applications and digital solutions. Individuals with a closer proximity to operations have a better understanding of end-user pain points, enabling them to efficiently translate requirements into features of the application, resulting in a more streamlined development process. Resulting from this experience, the organization involved in this experience is seeking to find further use cases where the use of low-code can result in increased productivity gains. The authors plan to report on these cases to build up more evidence and knowledge about the use of low-code in the construction industry.

It is reasonable to expect that, like other industries, the use of low-code platforms in the construction industry will grow and become more widespread. This resulting from several factors, including the increasing demand for digital solutions, the need for faster and more efficient construction processes, and the growing recognition of the benefits of low-code platforms. It is also expected that the capabilities of low-code platforms will continue to expand and evolve, enabling the creation of increasingly advanced and complex solutions. This may include the integration of cutting-edge technologies such as artificial intelligence and machine learning, further enhancing the transformative potential of low-code platforms in the construction industry.

In terms of the citizen developer, it is worth to note that the use of low-code also requires certain level of computing knowledge, including data modelling in order to proper delivery an application. Some authors even use the term “low-code” and “no-code" interchangeably (e.g., Hurlburt (2021)) which may be misleading considering the need of minimum computing knowledge to develop applications.

LOW-CODE TECHNOLOGY AND LEAN CONSTRUCTION

Lean construction philosophy seeks to minimize waste of materials, time, and effort to maximize the value delivered to customers (Koskela et al., 2002). In this regard, the use of the low-code/AI solution effectively supported the project team to remove unnecessary work from the process. Along with waste reduction, low-code also supports the team having relevant data available to learn and steer the project. It is known that that construction sites are very rich in terms of data, but most of this data remain analogue and it is barely used for the benefit of the project. By facilitating the data capturing and transformation process, low-code could be an enabler to support projects to better leverage the use of data, facilitating access to relevant Key Performance Indicators supporting the Plan-Do-Check-Act (PDCA) continuous improvement cycle. Our experience indicates that digital solutions or applications developed with low-code platforms do not generate new file types, but rather exploits existing file formats to facilitate interoperability across software. This helps integrate the fragmented software landscape and data silos rather than fragment them further.

Arguably, the type of technology behind the low-code/AI-powered solution described in this study is not ground-breaking. However, the value of the approach lies in the productive development practices that it enables. That is, lowering the technical barriers that allow individuals without advanced coding expertise to create digital workflows to streamline processes and harness the data available on construction sites. This approach provides an ideal environment for project teams to use technology to integrate the project delivery approach (Martinez et al., 2022), supporting both people and processes, in line with the principles of lean construction. (Liker & Meier, 2013).

As per the results of this experience, it is expected that the combination of lean construction and low-code platforms would have a substantial impact on the future of construction projects. The streamlined processes made possible by low-code and the reduction of waste made possible by lean construction are likely to result in quicker project completion times and increased customer satisfaction. This is because of the low-code platform's capacity to simplify data capture and transformation, hence enabling better data-driven decision making. In addition, the low technical barriers of low-code solutions will enable a larger number of individuals to engage in the implementation of technology, thereby contributing to the alignment of technology with lean processes.

Low-code platforms and lean construction are likely to become even more integrated as the construction industry continues to evolve. It is anticipated that the use of AI and other sophisticated technologies in low-code platforms would expand, hence enhancing project efficiency and decreasing waste (Cisterna, Lauble, et al., 2022). Additionally, the use of low-code solutions in construction will continue to expand beyond simple workflows to include complex, data-intensive applications. This includes, for instance, the integration of relational databases such as Microsoft Dataverse, allowing the design of more complex and intensive data models.

INTERFACES TO CONTEMPORARY CONSTRUCTION INDUSTRY TOPICS

While developing and implementing the solution described in this study, the authors also realized interfaces to other contemporary construction industry topics such as Industry 4.0, Building Information Modelling (BIM), and Digital Twin. The data which can be digitalized and processed using low-code/AI could be further exploited and integrated in a larger system. For example, data captured onsite could be linked to the BIM Industry Foundation Classes (IFC) schema to enrich data available in the model. These types of interfaces offer an interesting area for further research considering the novelty of low-code in the construction industry.

LIMITATIONS

The digital solution described in this study was developed using one of the many low-code development platforms currently available in the market. This platform was already embedded in the organizational information technology landscape. As a result, the low-code platform was ready to use, and there was no need to benchmark low-code solutions and spend additional time integrating it into the organization's systems. Although low-code platforms offer similar features, the outcomes of this study could have been influenced by the platform used. In this regard, comparing the suitability of the features of low-code platforms in the context of the construction industry is also an interesting field of study. This paper also describes a single use case. The authors encourage further exploring use cases and research to build up evidence about the benefits and limitations of low-code use in the context of the construction industry.

The solution could have also considered digitalizing delivery notes at the source. That means, requesting the supplier to manage delivery notes digitally, instead of printed. Arguably, this solution requires developing and onboarding suppliers on a shared digital platform. This is an idea to explore in the future. Nevertheless, the capabilities of the low-code platform to handle the requirements of this type of solution were not assessed in this study.

CONCLUSIONS

This paper explored the use of low-code and AI to improve processes in the construction industry context. Low-code enables people with no advanced coding skills to develop and deliver digital solutions to address specific business and operational challenges. This article delves into the potential of low-code technology in facilitating the digitalization of construction-specific processes and promoting lean construction practices in this field.

This study documented the development and implementation of a low-code and AI-powered solution to extract and process data from paper delivery notes, resulting in a 78% process time savings, and the availability of processed digital data related to the process. This experience highlights the importance of the low-code approach, particularly the involvement of individuals with a closer proximity to operations in the development process. This involvement enables the effective elicitation of requirements and their translation into features of the digital solution, ensuring that the result aligns with the process and meets the end-user's needs.

The use of low-code is gaining a tremendous momentum and scientific interest. Since it is a relatively new topic, there is significant room for further research. The authors encourage the development and documentation of additional case studies to build up evidence about the benefits and limitation of using low-code to support continuous improvement in the construction industry context. Additionally, there are several low-code platforms available with different features and capabilities. Further research could involve exploring the relevant requirements of a low-code platform that align with the specifics of the construction industry.

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UNLEASHING THE POWER OF CHATGPT FOR LEAN CONSTRUCTION: AN EARLY OUTLOOK

Makram Bou Hatoum[1] and Hala Nassereddine[2]

ABSTRACT

Artificial Intelligence (AI) is one of the core technologies that was brought forward by the fourth industrial revolution. This technology is disrupting industries all around the globe, and the construction industry is no exception. Research targeting AI in construction has grown exponentially in the last decade as researchers investigate how to leverage AI across the project lifecycle. With the recent release of ChatGPT, AI research is expected to grow even more as the construction industry navigates this breakthrough and understands its impact.

This paper focuses on AI in the context of Lean Construction and has two main objectives. First, the paper reviews the database for the International Group of Lean Construction (IGLC) to identify AI-related publications, summarize their findings, and detect the research trends. A total of nineteen papers were identified, presenting various theoretical and practical aspects of AI in Lean Construction. Second, the paper provides an early outlook into ChatGPT and experiments with its capabilities through three simple use cases that explore ChatGPT's ability to educate and train on Lean aspects, perform conceptual analysis, and develop Lean applications. The early interaction with ChatGPT showed promising potential for the construction industry with encouraging results that can empower the Lean community.

KEYWORDS

Lean Construction, Artificial Intelligence, ChatGPT, Construction 4.0.

INTRODUCTION

Artificial Intelligence (AI) is a disruptive technology that has the power to revolutionize industries. The concept of AI can date back to the early 1300s (Press, 2016) but its science was officially established in the early 1930s (Ertel, 2017). The term "Artificial Intelligence" was first coined in the year 1955 by McCarthy et al. (1955) "2 month, 10 man study of artificial intelligence" proposal which led to the birth of the AI field in 1956 (McCarthy et al., 2006). The birth was a result of a strong period of technological developments that was accelerated by World War II and the desire to understand and connect the functioning of machines and organic beings (Council of Europe, 2023).

While there is no standardized definition of AI, the notes of 10 U.S. Code § 2358 use the following definitions: "(1) Any artificial system that performs tasks under varying and unpredictable circumstances without significant human oversight, or that can learn from experience and improve performance when exposed to data sets; (2) An artificial system developed in computer software, physical hardware, or another context that solves tasks requiring human-like perception, cognition, planning, learning, communication, or physical

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action; (3) An artificial system designed to think or act like a human, including cognitive architectures and neural networks; (4) A set of techniques, including machine learning, that is designed to approximate a cognitive task; and (5) An artificial system designed to act rationally, including an intelligent software agent or embodied robot that achieves goals using perception, planning, reasoning, learning, communicating, decision-making, and acting."

AI AND THE CONSTRUCTION INDUSTRY

The construction industry is no exception to the disruptions caused by AI, a technology that is core to the Construction 4.0 transformation of the industry (Hatoum et al., 2021). A state-of-the-art review by Abioye et al. (2021) on AI in construction showed the valuable contribution of the technology to resource and waste optimization, supply chain management, health and safety analytics, estimation and scheduling, and job creation. The study also highlighted the potential to develop AI-driven contract comprehension, AI-driven audit systems for construction financials, AI-enabled head-mounted displays, voice user interfaces, and deep learning-based project assistive technologies (Abioye et al., 2021). Another study performed by Pan & Zhang, (2021) proposed a futuristic framework for construction engineering and management that builds on AI research and integrates it with other Construction 4.0 technologies such as robotics, AR, VR, IoT, blockchain, 3D printing, and digital twins, to enhance and optimize the design, planning, construction, and operation of projects. The importance of AI has also dubbed it as one of the ten emerging digital technologies in the Architecture, Engineering, Construction, and Operation (AECO) sector, as the interest in AI research has been growing almost exponentially in the past 10 years (Dou et al., 2023). Despite its importance however, major challenges remain at the level of cost, security, talent shortage, computer power requirements, internet connectivity requirements, policies and regulations, as well as ethical and cultural dilemmas (Abioye et al., 2021; Regona et al., 2022).

CHATGPT: AN AI BREAKTHROUGH

The release of ChatGPT in December 2022 has brought major disruptions, as its accessibility and capability prove that "AI is finally mainstream" (Vincent, 2022). ChatGPT is part of the Generative Pre-trained Transformer (GPT) family of languages developed by Open AI "which uses a transformer neural network to generate natural language text" (OpenAI, 2022). The model is trained using Reinforcement Learning from Human Feedback (RLHF), and unlike traditional chatbots, it can "provide answers, solutions, and descriptions to complex questions including potential ways to solve layout problems, write code, and answer optimization queries" (Haque et al., 2022; OpenAI, 2022) It can also remember what the user discussed earlier in the conversation for follow-up questions, refuse inappropriate requests, and question incorrect responses (Haque et al., 2022).

While the technology behind ChatGPT is not new and the model has several shortcomings, its impressive detailed and human-like text has made it a breakthrough in the AI chatbots that were ever released to the public, drawing more than 1 million users in its first five days and crossing the 100 million monthly users in January 2023 (Bæk, 2023) (Baek, 2023).

ChatGPT serves as the greatest example of the "Ready or Not, AI Comes" scenario, where its disruptions were rapidly noted in major aspects and industries (Lock, 2022; Roose, 2022). For example, concerns quickly grew over its effect on academia and research, prompting publishers to create policies on the use of ChatGPT in research articles, and causing universities and schools to constrain its impact on teaching, assignments, and examinations (Lock, 2022; Roose, 2022; Stokel-Walker, 2023).

As for the construction industry, the use of ChatGPT remains in its infant stages as researchers and practitioners are still trying to understand the technology and navigate its capabilities. Early articles by practitioners highlighted ChatGPT's power in helping construction professionals draft ideas, review communications, speed-up information inquiry, suggest solutions in various formats, highlight talking points, create document templates, fill templates with the required information, and automate administrative work (Mitchell, 2023; Sullivan, 2023). Another study conducted by Prieto et al. (2023) investigated the use of ChatGPT for scheduling construction projects. Results showed that while ChatGPT provided a logical sequence of tasks, its thought process behind the schedules was very linear. Not all of the proposed tasks agreed with the scope of work, but conversing with ChatGPT allowed it to correct some of its errors. The authors attributed the reason to the fact that ChatGPT has not been trained for specific construction purposes, making it not aware of all tasks that could be needed for construction. The study concluded that the overall performance was reasonable, the interaction experience with the interface was positive, and the results seem promising if ChatGPT can be further trained on specialized and specific construction project aspects (Prieto et al., 2023). The role of ChatGPT in generating construction schedules was also emphasized by Singh et al. (2023). The study highlighted the potential of ChatGPT as an aid for industry experts to create general project schedules while also acknowledging the tool's limitations in accounting for specific project constraints, risks, and requirements (Singh et al., 2023).

OBJECTIVE AND METHODOLOGY

With the importance of AI to the construction industry and the rise of ChatGPT, the objective of this study is to answer two research questions (RQs):

- ***RQ1.*** How is AI being researched in the context of Lean Construction?
- ***RQ2.*** Can ChatGPT benefit Lean Construction?

To answer RQ1, the database for the International Group of Lean Construction (IGLC) annual conferences was reviewed to identify all AI-related publications. The IGLC database was chosen because of its superior research in the field of Lean Construction and the significant impact of the IGLC annual conferences on the Lean community and the direction of Lean research. All AI-related publications were identified and summarized, and a keyword network was created to detect the general research trends of AI within Lean Construction.

As for RQ2, the authors conducted three simple use cases to experiment with ChatGPT and showcase its potential. The use cases explore ChatGPT's ability to educate and train on Lean aspects, perform conceptual analysis, and develop Lean applications. The use cases provide an early outlook into the capability of the technology and its support to the Lean construction community.

ARTIFICIAL INTELLIGENCE AND LEAN CONSTRUCTION

The first search within the IGLC database for papers that used the term "Artificial Intelligence" in their title, abstract, and/or keywords yielded nine publications. The second search for AI-related terms identified from the first search yielded eleven other publications.

PAPERS WITH DIRECT MENTIONS OF "ARTIFICIAL INTELLIGENCE"

The papers identified in the first search are summarized in Table 1. The nature of the papers varied between theoretical research and practical research. Theoretical research focused on AI's impact on the different Lean aspects like Lean principles and tools (Cisterna et al., 2022) and human-machine interaction (Arroyo et al., 2021), while the practical research utilized AI techniques to develop, verify, and validate AI models for different project purposes such as productivity (Zhao & Chua, 2003), and planning and scheduling (Benjaoran & Dawood, 2005).

A comprehensive keyword network was generated using VOSviewer for the papers as shown in Figure 1. The network aimed to identify the general themes of AI research by clustering the keywords using their association strength and detecting common key terms that

Lean construction researchers use in their papers. Each color in the network represents a specific cluster, and the following trends are identified:

- Commitment, collaboration, and trust are needed for AI to empower digitization through smart data analysis techniques;
- The proper integration of AI and Lean construction can foster a cultural change that embraces continuous improvement;
- Decision-making using AI must adhere to social and ethical principles, and decision-makers should consider and limit AI bias;
- The proposed AI models most used neural networks for multiple project aspects including planning, scheduling, production lines, productivity, and waste;
- Knowledge management was a frequently investigated area where AI techniques such as decision trees, machine learning, data mining, and neural networks were used to analyze data and information and develop knowledge management systems.

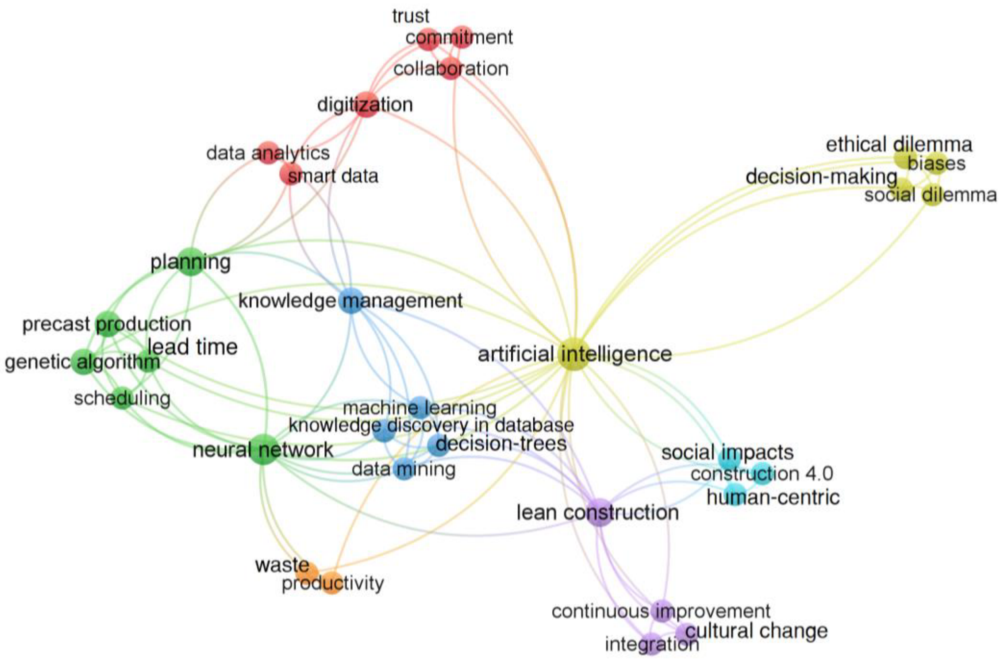

Figure 1: Keyword Network of the IGLC Papers that Used the Term "Artificial Intelligence"

PAPERS WITHOUT DIRECT MENTIONS OF "ARTIFICIAL INTELLIGENCE"

The network in Figure 1 highlighted frequent key terms for different AI techniques used by Lean construction researchers. The key terms include "Neural Networks", "Machine Learning", "Decision Trees", "Genetic Algorithm", "Data Mining", and "Knowledge Discovery". Each of these where used to search the IGLC database for additional AI-related papers, and the search yielded eleven publications that did not appear in Round 1.

The papers are summarized in Table 2. The research was mostly practical in nature with direct applications of multiple AI techniques such as machine learning applications to create information systems (Caldas & Soibelman, 2002), genetic algorithms to reduce inventory (Ko, 2011), and artificial neural networks to benchmark and predict environmental performance indicators (Fernandes et al., 2019). Moreover, some AI techniques were used with common Lean decision-making tools such as genetic algorithms with Analytic Hierarchy Process (Lin, Wang, & Yu, 2009) and graph-based inference with Choosing by Advantages (Haymaker, Chau, & Xie, 2013).

Table 1: Summary of AI-related papers published in IGLC (Round 1)

Paper	Summary
Soibelman & Kim (2000)	Presented a framework required for implementing Knowledge Discovery in Databases (KDD) to uncover new patterns in construction projects by examining extensive project data. The procedure comprises five main stages: identifying issues, preparing data, mining data, analyzing data, and refining the process. The paper also developed a prototype of the KDD system And experimented with it utilizing the Resident Management System database from the US Corps of Engineers.
Benjaoran & Dawood (2003, 2005)	Proposed a system for automatic planning referred to as "artificial intelligence planner (AIP)" to minimize lead time and enhance the scheduling and planning of the precast concrete production process. AIP relies on two AI techniques - genetic algorithm (GA) and artificial neural networks (ANN). The original planner consists of four components that carry out different functions but communicate automatically with each other to achieve the AIP's overall purpose: "the central database, graphic data extractor, processing time estimator, and production planner". The authors followed it up with another paper where they enhanced AIP and presented a case study.
Zhao & Chua (2003)	Utilized a neural network to model the influence of wastes on measured productivity. The study formalized 20 types of waste, then analyzed a total of 75 sets of productivity data collected from formwork crews on multiple projects over 6 months. The model was able to successfully identify the 8 critical wastes affecting productivity and predict on-site performance with very good accuracy.
Oprach et al. (2019)	Focused on understanding the challenges in scheduling construction tasks with smart data and identifying possible solutions using existing applications of AI. The paper suggested three solutions including (i) naming of work packages by clustering with semantic wikis, (Sequential) pattern mining, and data recording with electronic devices; (ii) improvement of activity duration data by recording data with robots and drones and analyzing it with machine learning; and (iii) defining operationally significant locations through using BIM.
Schia et al. (2019)	Researched the successful implementation of digital tools and the understanding of human-machine relationships using literature, a case study, and interviews. The study utilized findings to provide technology, process, and culture factors that can "close the gap between the current and future use of AI in the construction industry" and evaluated the factors on three digital tools – Touchplan, Synchro, and ALICE
Arroyo et al. (2021)	Explored the ethical and social considerations of the AI application to spark discussion on AI within the Lean community. The study presented different examples, opinions, and use cases to elaborate on five main discussion points including (i) verifying the source of data and means of the data collection; (ii) trusting AI decisions; (iii) understanding AI bias; (iv) being cautious of pleasing the algorithm; and (v) understanding the impact on project team motivation and decision-making.
Cisterna et al. (2022)	Investigated the synergies between AI methods and Lean construction techniques where they highlighted two types of synergic interactions – interactions where Lean supports AI processes and interactions where AI supports Lean techniques. Findings were presented in an AI-Driven Construction Improvement Process (CIP) framework in which people were elevated to a pivotal position as a unifying element between the two fields.
Noueihed & Hamzeh (2022)	Explored the social impact of adopting Construction 4.0 technologies and addressed AI as a specific case of these technologies. The study emphasizes the need for human-centric approaches where technologies are means to support people to flourish and succeed, and should not be treated as means for dominancy. The study also highlighted that people should drive the design and implementation of technologies to make sure that "technologies fit their needs and preserve their rights of performing work freely, efficiently, and humanely".

Table 2: Summary of AI-related papers published in IGLC (Round 2)

Paper	Summary
Caldas & Soibelman (2002)	Utilized automated text classification methods to support the "implementation of pull techniques in construction management information systems". The proposed system comprises six main modules namely: "data collection, data conversion, data preparation, dimensionality reduction, learning, and classification". Multiple machine-learning algorithms were used in the learning module including Support Vector Machines. The prototype was created to automate the stages involved in the document classification process and enabled the generation of classification models for projects based on user-defined project components.
Filho et al. (2004)	Analyzed a large data set from a capital facility project to detect common patterns of sequences of non-completed activities. The analysis showed effectiveness in identifying problems in the production workflow and pinpointing relevant events that had not been noticed by the onsite workforce.
Bortolazza, Costa, & Formoso (2005)	Aimed to provide insights into the Last Planner System implementation in Brazil using a quantitative approach. The study aimed to analyze the percentage of plans completed (PPC) data from 115 residential, industrial, and low-income housing projects. The study also utilized data mining techniques including decision trees and neural networks to detect patterns and analyze causes for the non-completion of work packages. The major preliminary reasons indicated that most projects had limited success in the implementation of look-ahead planning.
Wu & Soibelman (2006)	Presented a case study on a novel approach developed by the authors to preprocess and represent network-based work plans from a project control system into abstraction-type descriptions in support of graphical analysis and pattern recognition. The analysis was performed on a Last Planner database of production control from a large capital facility project. The resulting patterns can allow project managers to better understand potential problems and make informed decisions to decrease variability and increase reliability in planning and control.
Srisuwanrat & Ioannou (2007)	Presented a unique investigation of lead-time buffering by focusing on "when to start a production line so that there is no interruption". Two distinct methods of lead-time buffering were investigated – the "sequence step algorithm" (SQS-AL) and the "completed unit algorithm" (CU-AL). The authors employed STROBOSCOPE coupled with a search add-on that utilizes a genetic algorithm (GA). Results showed that incorporating a lead-time buffer leads to improved workflow and greater project profit that vary based on the workflow interruption's penalty cost and indirect cost. The study highlighted the algorithms' advantages as well as limitations "depending on assumptions, simplicity of the simulation model, project characteristics, and uncertainty".
Ko & Wang (2008)	Developed a flow-shop sequencing model to enhance weekly work planning. The model considers production constraints and buffer sizes and uses a genetic algorithm with multiple objectives to explore optimum solutions that minimize both makespan and tardiness penalties.
Lin et al. (2009)	Proposed an integrated model to facilitate the weightings and evaluation of "tenders involved in the best-value contractor selection process". To weight criteria, an adaptive Analytical Hierarchy Process (AHP) was developed using a soft computing scheme and genetic algorithms "to recover the weights of the various criteria based on the derived pairwise weighting matrix". As for tender evaluations, the authors proposed "a bid price evaluation submodel" to handle the quantitative criteria and "a performance-based evaluation submodel" to quantify the anticipated performances of other qualitative criteria for every bidder.

Paper	Summary
Ko (2011)	Developed a framework to reduce the precast fabrication inventory without changing production resources. The framework comprises three components including "(i) a time buffer evaluation is to avoid fabricators losing capacity by considering demand variability; (ii) a due date adjustment to shift the production curve closer to erection dates and reduce inventory; and (iii) a scheduling component that arranges production sequences to achieve multi-objectives using genetic algorithms".
Haymaker et al. (2013)	Leveraged decision models and machine learning to support designers in dealing with decision-making challenges by automatically retrieving pertinent information from prior decisions. The authors employed the Belief Propagation (BP) graph-based inference to "develop a collaborative decision-making model" based on the Choosing by Advantages (CBA) methodology. The paper proposed the CBA-PB algorithm and implemented it to validate its efficiency and effectiveness.
Antunes & Poshdar (2018)	Suggested a theoretical framework to tackle construction production issues through the implementation of "an integrated automatic supervisory control and data acquisition for management and operations". The system is segmented into planning, controlling, executing, and monitoring groups to track the project product as well as production. The system also employed machine learning models that can be trained with input sources from technologies to perform tasks and generate outputs that feed into the system.
Fernandes et al. (2019)	Proposed an equation that "predicts environmental performance indicators based on construction progress". The model was developed via Python and utilized artificial neural networks using a database of 15 construction sites. Three equations were proposed for three environmental indicators – water consumption, energy consumption, and waste generation. The equations can provide managers with a benchmark to establish environmental performance targets and make managerial decisions as the construction progresses.

CHATGPT AND LEAN CONSTRUCTION

To understand how can ChatGPT benefit Lean construction professionals and researchers, the authors performed three simple use cases to experiment with the technology's capabilities.

USE CASE ONE: EDUCATION AND TRAINING

The authors asked ChatGPT to define Lean Construction, list the major concepts and practices, and explain how ChatGPT can support the Lean Construction field. The responses are shown in Figure 2 (Left). The answers provided were both accurate and reliable. The authors also asked ChatGPT to provide the answer to Question 2 (Lean concepts and practices) in the form of an official training document, and ChatGPT changed the entire answer to a professional training template.

USE-CASE TWO: CONCEPTUAL ANALYSIS

The authors provided ChatGPT with a descriptive steel erection process beginning from the time the material was ordered and shipped from the manufacturer, through the construction production process, and ending with the material in its final position in the facility. The process was adopted from the Construction Industry Institute (CII) project RT-191. The authors requested ChatGPT to identify Lean waste and provide solutions, and the responses are shown in Figure 2 (Right). ChatGPT was successfully able to identify five waste types and provide solutions that meet the scope of the process. The answer provided by ChatGPT was very impressive given that ChatGPT was only given a descriptive summary of the process without any quantitative data for further analysis.

Authors: *Define Lean Construction.*
ChatGPT: "Lean construction is a management philosophy and production approach that aims to optimize the design and delivery of construction projects. It is based on the principles of the Toyota Production System, which has been successfully applied in manufacturing and other industries. In construction, the goal of lean construction is to eliminate waste, increase efficiency, and improve overall project performance by involving all members of the construction team in the continuous improvement process. This is accomplished through a series of tools and techniques, including value stream mapping, pull planning, and kaizen events, that help identify and eliminate non-value-adding activities. Lean construction also places a strong emphasis on collaboration and communication between all stakeholders in the project, including owners, designers, contractors, and subcontractors. The focus is on delivering projects that meet the needs of the customer, while also improving quality, reducing costs, and shortening the construction timeline."

Authors: *List the main Lean construction concepts and practices.*
ChatGPT: "The main concepts and practices of lean construction are as follows:
- Elimination of waste: Lean construction aims to eliminate waste in construction processes, including overproduction, waiting, defects, overprocessing, excess inventory, unnecessary motion, unused talent, and production of unnecessary products.
- Continuous improvement: Lean construction is focused on continuous improvement, which involves regularly reviewing and refining construction processes to identify and eliminate waste, and improve efficiency and quality
- Value stream mapping: This involves creating a visual representation of all the activities and processes involved in a construction project, from start to finish, to identify areas for improvement and eliminate waste.
- Just-in-time (JIT) production: JIT production is a key concept in lean construction, and involves producing materials and components just in time for when they are needed on the construction site, reducing the need for storage and inventory.
- Pull production: This involves producing materials and components in response to actual demand, rather than producing ahead of time, to reduce waste and improve efficiency.
- Kaizen: Kaizen is a Japanese term for continuous improvement, and involves regularly reviewing and refining construction processes to eliminate waste and improve quality and efficiency.
- Total productive maintenance (TPM): TPM involves involving all employees in the maintenance of equipment and machinery, to ensure that they are maintained in good condition, and to reduce downtime and waste.
- 5S: 5S is a set of five principles for workplace organization and efficiency, which include sorting, simplifying, sweeping, standardizing, and sustaining.
- Visual management: This involves using visual aids, such as visual schedules and status boards, to communicate project information and improve collaboration and communication.

In summary, these are the main concepts and practices of lean construction, which aim to eliminate waste, improve efficiency and quality, and promote continuous improvement in construction processes."

Authors: *How can ChatGPT support and enhance Lean Construction?*
ChatGPT: "ChatGPT can support and enhance the implementation of lean construction in several ways:
- Education and training: ChatGPT can be used as a virtual assistant to provide education and training to construction professionals on the principles and practices of lean construction. This can help to increase awareness and understanding of lean construction, and promote its adoption in the industry.
- Project management: ChatGPT can assist in the management of construction projects by providing real-time information and support to project teams. For example, it can help with the creation of project schedules, tracking of project progress, and identification of areas for improvement.
- Collaboration and communication: ChatGPT can facilitate collaboration and communication between all stakeholders in a construction project, including owners, designers, contractors, and subcontractors. This can help to promote teamwork, increase transparency, and reduce misunderstandings, which are key components of lean construction.
- Data analysis: ChatGPT can assist in the analysis of data related to construction projects, such as construction schedules, costs, and quality metrics. This can help to identify areas for improvement, and support the implementation of continuous improvement initiatives in the field.
- Knowledge management: ChatGPT can help to centralize and manage knowledge related to lean construction, allowing construction professionals to access and share information, best practices, and lessons learned.

In summary, ChatGPT can be a valuable tool for promoting and enhancing the implementation of lean construction in the construction industry. By providing support for education and training, project management, collaboration and communication, data analysis, and knowledge management, it can help to increase the efficiency and effectiveness of construction projects, and support the continuous improvement of construction processes."

Authors: The following paragraphs describe a structural steel erection process, beginning from the time the material was ordered and shipped from the manufacturer, through the construction production process, and ending with the material in final position in the facility. Information on delivery and handling of the steel joists was obtained from the project manager. Once it arrived onsite, the basic flow of the steel was as follows:
1. After the steel was manufactured, it remained onsite at the manufacturer's warehouse until needed.
2. Each steel shipment consisted of all structural steel members required in one bay. Steel could not be stored onsite in a large material lay-down yard due to safety restrictions. The steel for three to four bays was stored on truck trailers (minus the cab) in the parking lot until needed. It usually remained in the parking lot for one week before being handled again and moved to the second staging area - a small material lay-down area next to the bay being erected.
3. Each load was handled by a heavy-duty forklift. Depending on the steel member type, one to three separate lifting actions were needed by the forklift operator to remove the entire load from the truck bed.
4. The load from the truck was placed on the ground in the same manner as it was on the truck. No shakeout occurred from the truck to the ground.
5. The piles from the truck were organized by member type (columns with columns, trusses with trusses, etc.).
6. Each steel member had a number that correlated to a number on the drawings. Following the placement of each pile on the ground, a ground crewman located the number on each steel piece and related it back to the foreman. This number helped the erection crew foreman with the proper erection sequence.
7. No shakeout occurred after placement on the ground. The crane was required to swing over the material lay-down area in random picks to reach each steel piece. One piece was picked at a time. This created a large material transport time for the crane operator.
8. After the steel members were placed near their respective bay staging areas, the crane moved the girders, bar joists and columns from the staging position to final position in the structure.

Please identify all Lean waste in this procedure and suggest solutions.

ChatGPT: The following are the identified sources of Lean waste in the structural steel erection process:
- Waiting: The steel was stored at the manufacturer's warehouse until needed, and then in the parking lot for one week before being moved to the next staging area, resulting in waiting time for the material to be used.
- Excess Inventory: Steel for three to four bays was stored on truck trailers, creating excess inventory and taking up valuable space.
- Overprocessing: Depending on the steel member type, one to three separate lifting actions were needed by the forklift operator to remove the entire load from the truck bed, leading to overprocessing and increased handling time.
- Unnecessary Motion: The crane was required to swing over the material lay-down area in random picks to reach each steel piece, resulting in unnecessary motion and increased material transport time for the crane operator.
- Unused Talent: The ground crewman who located the numbers on each steel piece was only utilized in the material handling process and not in any other value-adding activities.

To eliminate these wastes, the following solutions can be considered:
- Reduce waiting time: Arrange for just-in-time (JIT) delivery of the steel members, so that they are delivered only when needed on the construction site, reducing the waiting time for the material to be used.
- Minimize excess inventory: Store only the necessary steel members required for the current bay in the parking lot, reducing the amount of excess inventory stored onsite.
- Streamline material handling process: Use equipment and processes that minimize the handling time of the steel members, such as using cranes to remove the entire load from the truck bed in one lift.
- Eliminate unnecessary motion: Arrange the material lay-down area in a way that reduces the movement required by the crane operator to reach each steel piece, such as organizing the piles by member type.
- Utilize all personnel: Encourage the ground crewman to take on additional responsibilities, such as assisting the crane operator, to utilize their full potential and skills.

Figure 2: Use-Case I (Left) and Use-Case II (Right)

USE-CASE THREE: APPLICATIONS DEVELOPMENT

The authors asked ChatGPT to code an application that can help Lean professionals fill in constraint logs. No details, descriptions, or any sort of information were provided for the application. In its reply, ChatGPT acknowledged that it cannot code the entire application, but it can provide a foundation to start developing it. The output resulted in a Graphic User Interface that allows the user to select the constrained type from a dropdown, describe the constraint, and specify its start and end date. Once the user clicks Submit, the input is exported to a text file. The use case showed the creativity of ChatGPT in developing applications. Another interesting aspect of the code is that ChatGPT utilized comments to explain the different sections of the code and their functionalities. This can make it easy for the user to understand the code when implementing and building up on it.

Unfortunately, I am not able to write a complete application for you, as it would require a significant amount of time and resources. However, here is some sample code that demonstrates how you could create a fillable form for constraint logs and track reliable promises in a construction project using the Python programming language:

```
# import necessary libraries
import tkinter as tk
from tkinter import ttk

# create the main window
root = tk.Tk()
root.title("Construction Project Constraint Log")

# create the frame for the constraint log form
frame = ttk.Frame(root, padding="10 10 10 10")
frame.grid(column=0, row=0, sticky="WENS")

# create the form fields
constraint_type = ttk.Combobox(frame, values=["Material", "Labor", "Equipment", "Weather", "Permits"])
constraint_type.grid(column=1, row=0)

constraint_description = ttk.Entry(frame)
constraint_description.grid(column=1, row=1)

start_date = ttk.Entry(frame)
start_date.grid(column=1, row=2)

end_date = ttk.Entry(frame)
end_date.grid(column=1, row=3)

# create the form labels
ttk.Label(frame, text="Constraint Type:").grid(column=0, row=0, sticky="W")
ttk.Label(frame, text="Constraint Description:").grid(column=0, row=1, sticky="W")
ttk.Label(frame, text="Start Date:").grid(column=0, row=2, sticky="W")
ttk.Label(frame, text="End Date:").grid(column=0, row=3, sticky="W")

# create the submit button
submit_button = ttk.Button(frame, text="Submit", command=lambda: log_constraint(constraint_type.get(),
constraint_description.get(), start_date.get(), end_date.get()))
submit_button.grid(column=0, row=4, columnspan=2, pady=10)

# create the function to log the constraint
def log_constraint(constraint_type, constraint_description, start_date, end_date):
  # add the constraint information to the constraint log
  with open("constraint_log.txt", "a") as log_file:
    log_file.write(f"{constraint_type} | {constraint_description} | {start_date} | {end_date}\n")

# run the main loop
root.mainloop()
```

This code creates a GUI application using the tkinter library that allows you to log constraints and track reliable promises in a construction project. The form includes fields for constraint type, constraint description, start date, and end date, and a submit button that adds the constraint information to a text file named constraint_log.txt.

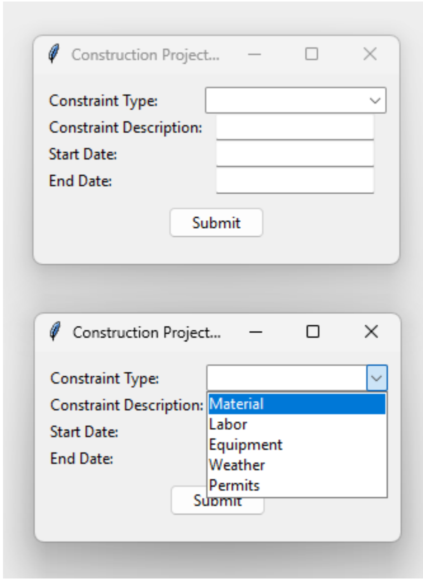

Figure 3: Use-Case III (code on the left and output on the right)

DISCUSSION

The review of the IGLC database on AI-related research showed that the Lean community has been invested in AI as early as the year 2000. Different publications have targeted both practical and theoretical research ranging from developing AI applications and models to understanding the implications of AI on people and Lean culture. With ChatGPT bringing AI to the mainstream, the research of AI within the Lean community is expected to rise even more. ChatGPT shows promising potential, and the three simple use cases presented in this paper showed a glimpse of how capable the technology can be for Lean Construction.

As illustrated in Figure 4, To successfully exploit ChatGPT and upcoming AI disruptions, Lean construction should embrace two types of people: innovators and doubters. On one hand, innovators represent individuals who will adopt ChatGPT early and will be eager to pilot the technology on different Lean aspects. They are often willing to take risks and embrace change, which can lead to new opportunities that leverage ChatGPT and AI in Lean Construction. On the other hand, doubters are individuals who are more cautious and skeptical of AI and ChatGPT. They will often want to understand the potential risks and downsides before embracing new ideas. The presence of both adopters and doubters will thus create a continuous improvement culture, where innovators will bring in new ideas and approaches to solving problems, while the doubters will help ensure that these ideas are thoroughly tested and evaluated before implementation. This interactive dynamic will result in a more thorough and well-informed use of the technology that enables trust, respect for people, adherence to ethical and social principles, and process enhancements.

The biggest threat to technology is resistance, a problem that remains widely common in the construction industry. Once doubters turn into resistors, the continuous improvement cycle of the technology will break as innovators will push ideas and resistors will block them. Thus, the Lean community needs to keep an open mind and embrace its scientific thinking to develop a community of innovators and doubters and exploit the potential of transformative technology.

Moreover, it is also important to acknowledge that AI tools like ChatGPT are still in their early stages of development and, as with any other technology, are expected to evolve and improve over time. Thus, in the meantime, it remains important to utilize the technology as intended, consider its limitations, and verify and validate its output using human intuition, expertise, and available AI content detectors.

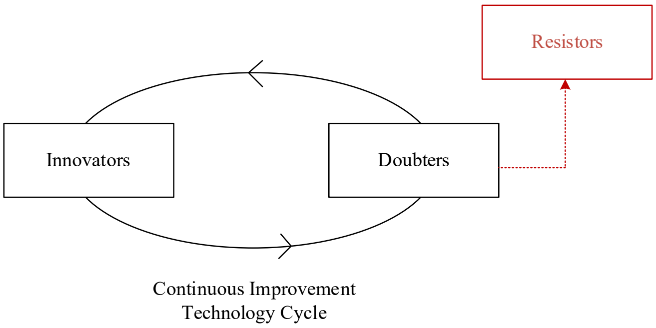

Figure 4: Conceptual Framework that Illustrates Lean and ChatGPT

CONCLUSIONS

This paper explored AI research in Lean Construction and presented preliminary findings on ChatGPT. A review of the IGLC database showed that AI has gained a lot of interest in Lean construction research, while the use cases on ChatGPT showed promising potential for Lean construction. The study however was limited to reviewing IGLC proceedings and performing simple use cases. Further studies can perform systematic literature reviews on other research databases to detect further trends. Future research is also expected to utilize ChatGPT in more complicated use cases that can fully leverage AI capabilities. Finally, in the words of ChatGPT:

Lean construction, so efficient and fast. A building process that's built to last.
With principles to eliminate waste. It aims to make every project great.
Along comes ChatGPT, a tool so bright. Bringing artificial intelligence to the site.
With its vast knowledge, it can assist. Making Lean construction more persistent.
Together they work, as a perfect team. Improving building processes like a dream.
Efficiency and accuracy are their goals. Building better structures for all roles.

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LEAN CONSTRUCTION AND BUILDING INFORMATION MODELING (BIM) IN DESIGN MANAGEMENT: SURVEY RESULTS FROM FRENCH COMPANIES

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ABSTRACT

Lean and BIM integration in the design phase may help achieve better design deliverables on the planned time and cost and consistent with the client's needs and requirements. With the absence of enough studies about lean-BIM integration in France, this study reports the results from a survey about lean-BIM integration in French design firms. The results of the study showed that lean is still not routinely adopted in these firms, and more than 95% of the firms do not provide training on lean. The evaluation of lean-BIM integration was neither high nor low; with a mean of 3.73 out of 5.00. Additionally, the results showed that BIM has still not delivered its full potential in the studied firms. The analysis of the results showed also a positive and significant impact of lean-BIM integration on design performance.

KEYWORDS

Lean construction, Building Information Modeling (BIM), Design Management, Construction, Lean construction 4.0, France.

INTRODUCTION

It is widely believed that decisions in the design phase of construction projects result in changes that cannot be adjusted without affecting the time, cost, and/or quality of the project (Haponava & Al-Jibouri, 2009; Sweis et al., 2008). As a result, design management is believed to be a critical factor that affects the success of construction projects (Chaize et al., 2022; Hattab & Hamzeh, 2013).

Design management refers to the planning, organization, and management of processes, people, knowledge, and information flow during the design phase to meet the client's needs and requirements (Herrera et al., 2020, 2021). During this phase, specialists from different disciplines work to translate the value proposition by the clients, meet their expectations, comply with the standards and avoid making errors in the design (Hattab & Hamzeh, 2013; Tauriainen et al., 2016). Nevertheless, achieving all these objectives is still questionable in the presence of weak and traditional design practices (Tauriainen et al., 2016).

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Traditional design management can be understood as a linear process that includes a set of tasks done by designers who work fragmentedly to deliver the design based on a predetermined schedule and due dates (Khan & Tzortzopoulos, 2015). In this understanding, collaboration and interrelations between design teams are unappreciated (Tauriainen et al., 2016). It also indicates that design continuous improvement is not the focus. This is due to the understanding that the linear design process helps to achieve higher productivity in design and the iterative approach, which normally contributes to improving value and innovation, is wasteful (Abou-Ibrahim & Hamzeh, 2016; Khan & Tzortzopoulos, 2015). Another consequence of this understanding is the neglect of the flow of information between the right people at the right time, which may result in design errors (Hattab & Hamzeh, 2013).

The presentation of Building Information Modeling (BIM) and lean thinking to design management is expected to solve these problems. The use of BIM offers opportunities to collaboratively work on a "live" version of the design between stakeholders and helps to increase transparency and information flow between all the stakeholders (Hattab & Hamzeh, 2013). The features of BIM allow for achieving numerous improvements in the design phase such as the decline in design errors and clashes, increased visualization, quicker and easier design alternatives, reduced design cycle time, improved coordination, and easier cost estimation (Herrera et al., 2021; Rojas et al., 2019; Tauriainen et al., 2016).

Nevertheless, BIM as a technology is not sufficient to ensure successful design management. Lean construction, with its principles and tools, helps to facilitate the generation of the value of the client and improve the social system during the design process. For instance, the presentation of the Last Planner System (LPS) during the design process can contribute to improving transparency, communication, trust, efficiency, and quality of the design (Chaize et al., 2022; Hamzeh et al., 2009; Khan & Tzortzopoulos, 2015). Big room/iroom/co-location is also effective to increase collaboration, decreasing design errors, and reduce latency in decision-making (Tauriainen et al., 2016) and Design structure matrix (DSM) is helpful to improve planning for the entire design phase (Rosas, 2013).

Therefore, the lean-BIM integration has been topical in many research works and applications (Abou-Ibrahim & Hamzeh, 2016; Bolpagni et al., 2017; Dave et al., 2013; Hattab & Hamzeh, 2013; Herrera et al., 2021; Mollasalehi et al., 2016; Rojas et al., 2019; Sacks et al., 2010; Tauriainen et al., 2016; Uusitalo et al., 2019). In France, a limited number of investigations have been carried out about this integration. Additionally, there is still some missing information about the adoption of both concepts in all phases of the construction despite different calls to adopt them (Chaize et al., 2022; Joblot et al., 2017; PLANBIM, 2022; Tranchant et al., 2017). Additionally, despite the global efforts to study lean-BIM integration, there has still insufficient studies that link between lean-BIM integration and design performance. Aiming at increasing the understanding of lean-BIM integration in France and its impact on design performance, the current study tries to achieve the following two objectives:

1- To investigate the levels of lean and BIM adoption in French design companies.
2- To study the impact of lean-BIM integration of design performance.

RESEARCH METHODOLOGY

To achieve the two objectives of the study, a survey to collected quantitative data was developed based on studies from the literature. The use of survey is very common when the researchers try to get quantitative insights about the personal perceptions and the organizational policies and practices (Albalkhy & Sweis, 2022). The survey included four main sections as follows:

1- Section 1: general information about the company and respondents (three questions; participants' experience, company size, and role in the company).
2- Section 2: was about BIM purposes and uses. This section included 12 questions that were adopted from the studies of Bolpagni et al (2017) and Herrera et al (2021). The

questions were about the experience of BIM adoption and training, purposes of BIM, and frequency of BIM uses on a five-point Likert scale from 1 (refers to never) to 5 (refers to always).

3- Section 3: was about lean principles and tools and was based on lean adoption and training and used tools. The section included three main questions that were adopted from the study of Bolpagni et al (2017).

4- Section 4: was about lean-BIM integration in design and evaluation of design performance. The section was based on eight questions adopted from the studies of Dave et al (2013) and Herrera et al (2021). For the lean-BIM integration, the questions were based on a five-point Likert scale where 1 (refers to never) to 5 (refers to always), while for the performance, the scale was from 1 (refers to strongly disagree) to 5 (strongly agree).

The survey was translated into French and developed using Microsoft forms. It was then distributed using emails and LinkedIn was filled by respondents from design and engineering studies firms in France. The analysis of the results was done using Microsoft Excel 2019.

ANALYSIS OF THE RESULTS

Participants and company profile

49 participants answered the questions of the survey. The analysis of the results showed that the vast majority of the respondents had a long experience in construction design and studies as 40 participants had more than 10 years of experience in the field. The roles of the participants ranged between directors, project managers, BIM managers, heads of departments, architects, engineers, and one lean manager.

Concerning the companies' profile, the participants represented the different sizes of companies as 21 participants were from companies with more than 100 employees, 7 were from companies with 50-100 employees, 13 were from companies with 10-50 employees, and 8 were from companies with less than 10 employees. The participants were also from companies with different areas of work including architecture, public and infrastructure projects, residential and real-estate projects, industrial buildings, commercial buildings, hotels, and renovation projects.

BIM adoption and uses

The responses regarding BIM adoption showed an acceptable range of BIM adoption as most of the participants stated that BIM had been applied in their companies for at least five years (38 respondents). Only one participant in the study stated that BIM was still not adopted in the company. Two other participants stated that BIM was new to their company and its adoption started less than one year ago. 38 respondents (78%) declared that their companies were offering training on BIM.

Regarding the purposes of BIM implementation, architectural purposes (n= 38 respondents), structural (n=25), mechanical (n=25), and plumbing (n=25) works were the most found motives for BIM adoption in the studied companies. BIM was also used to manage and develop electrical works, maintenance and alarm systems, facades, environmental studies, and others.

Concerning the BIM applications in the design phase, Figure 1 shows that 3D coordination (mean=4.16), code validation (mean=3.76), and cost estimation (mean=3.02) are among the most frequent uses of BIM in the studied firms. While 4D planning (mean=1.96) is the least frequent use of BIM.

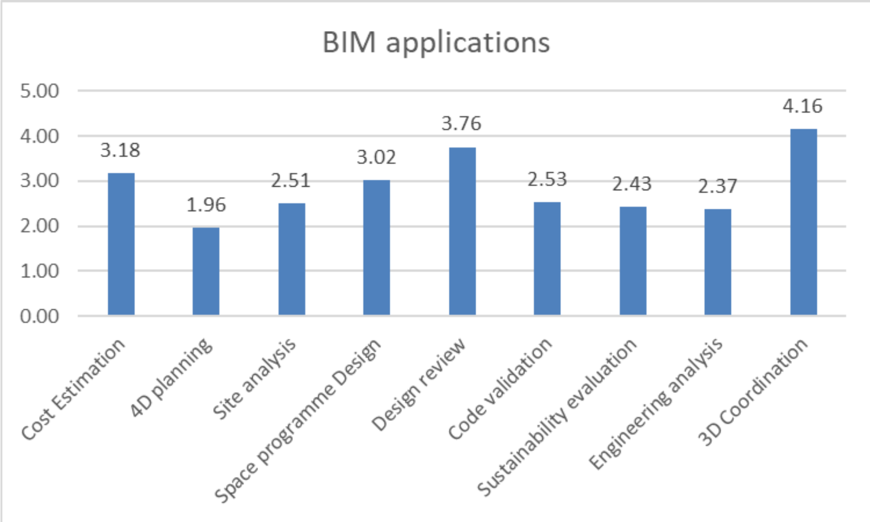

Figure 1: BIM uses in the design phase

Lean adoption and lean tools

The adoption of lean was significantly less in comparison to BIM. This is because only 11 participants (22.45%) stated that lean was adopted in their firms. Among them, only one firm was adopting lean for more than ten years and eight firms were adopting lean for 1-5 years. Additionally, only two participants stated that their companies provide training on lean.

Nevertheless, despite the lack of a declaration of lean as a whole philosophy, some participants believed that their companies use some tools that might facilitate the future implementation of lean. More specifically, as illustrated in Figure 2, the participants showed that the most applied tool/practice is the A3 problem-solving reports (n=13), then Big room or co-location to improve collaborative planning and design (n=12), and then the last planner system (LPS) (n=10). Other tools such as design structure matrix (DSM), plan-do-check-act (PDCA), value stream mapping (VSM), and 5S were less implemented. The least implemented tools/practices were the target value design (TVD), which was implemented by two companies, and the integrated project delivery (IPD), which was implemented by only one company.

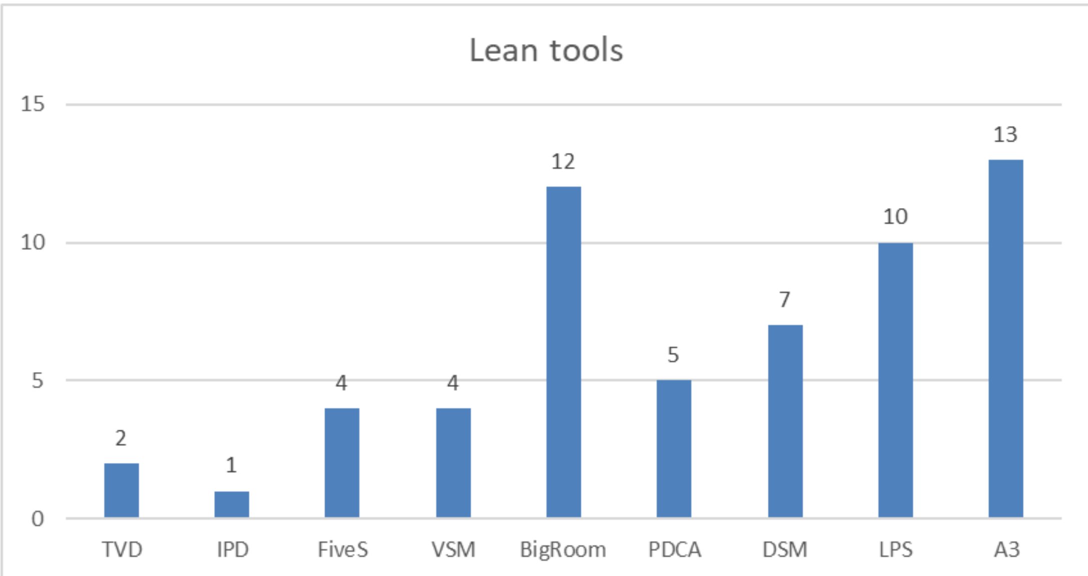

Figure 2: Applied lean tools/practices

Lean-BIM design management

Lean-BIM design management in this study refers to the integration between lean and BIM and the use of BIM models to support lean principles. Table 1 shows that the overall evaluation for lean-BIM integration was neither very high nor low as the mean was 3.73 out of 5.00. The highest evaluation was for the client value (mean= of 3.77), while the lowest was for the early involvement of construction stakeholders (mean= of 3.09). In this regard, it is apparent that other stakeholders (e.g. contractors and suppliers) are not involved early enough before the end of the design phase.

The results also show that design firms try to continuously evaluate and refine the design aiming at satisfying the needs and requirements of the client (mean=3.98). Nevertheless, the use of early BIM models for this purpose is still insufficient (mean=3.55). Concerning BIM as well, BIM models do not seem to be fully implemented to facilitate improving constructability in the later phases (mean=3.29). They are better used for visualization and assessment of design alternatives (mean=3.69) and for collaborative planning among the design teams (mean=3.8).

Table 1: Lean-BIM design management

Dimension	**Item**	**Mean (std. dev)**	**Dimension means (std. dev)**
Client value	Instead of one brief of requirements by the client, the early design is developed iteratively. In each iteration, the requirements of the client are evaluated and the design is refined	3.98 (1.051)	3.77 (1.010)
	BIM models are used to develop the early design to help evaluate the requirements of the client	3.55 (1.385)	
Set-based strategy	Designers consider sets of alternatives from the start of the design process rather than developing one alternative at the beginning	3.65 (1.200)	3.67 (0.927)
	BIM is used to enable rapid visual creation, communication, and assessment of project alternatives	3.69 (1.158)	
Early-involvement of stakeholders	Major project stakeholders (e.g. contractors, suppliers…) are involved early in the design process	2.90 (1.177)	3.09 (1.024)
	BIM models are used in the design phase to help stakeholders plan and construct the building virtually	3.29 (1.275)	
Collaborative planning	BIM models for all design teams can be combined periodically for collaborative working and analysis	3.80 (1.190)	3.64 (0.930)
	The client regularly participates in meetings to support decision-making and problem-solving	3.49 (1.063)	
Overall Mean	**Lean-BIM design**	**3.73 (0.890)**	

Design performance

The analysis of the results showed that the overall performance of the design in the studied firms was neither high nor low as the mean was 3.66 out of 5.00. As shown in Figure 3, the highest evaluation was for the indicators related to the client; specifically, for understanding the needs and requirements (mean=4.22) and then for achieving the client's satisfaction (mean=4.06). As the results showed, participants believed that they could also avoid future change orders (mean=4.04).

The figure also shows that the lowest evaluation was for clash detection (mean=2.76), and then for engaging design teams (mean=3.00), the flexibility of decision-making (mean=3.02), and easiness of dealing with design changes (mean=3.04). The results also showed that delivering the design in compliance with the planned time and budget was not easy (means= 3.10 and 3.18 respectively).

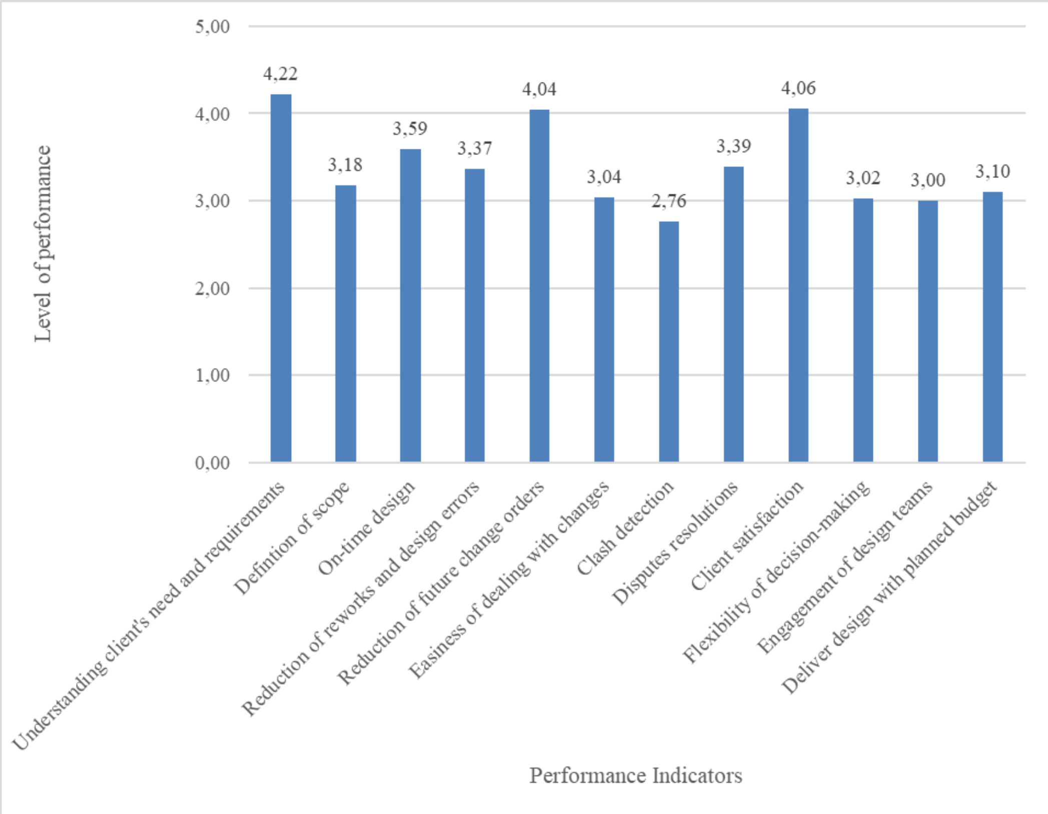

Figure 3: Design performance evaluation

To study the relationship between lean-BIM integration and design performance, a simple linear regression analysis was conducted. The regression test (as shown in Figure 4) revealed that at a significance level of (α=0.050), there is a positive and significant impact (P-value= 0.020) for lean and BIM integration in the design phase on design performance. The coefficient of correlation for the relationship is (r=0.44) and the coefficient of determination is (R-square= 0.194). This means that 19.4% of the change in the design performance can be explained by the change in the lean-BIM integration. Despite the significance of the relationship, it is worth mentioning that the the relationship needs to be investigated and validated using different and larger sample sizes and using other regression analyses.

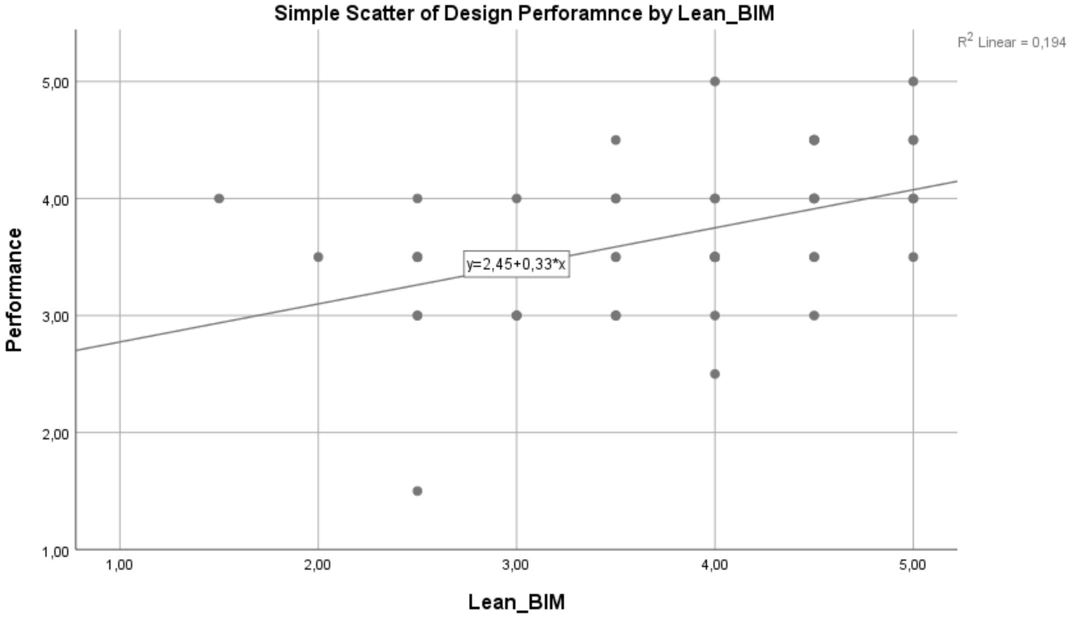

Figure 4: Relationship between Lean-BIM integration and design performance.

DISCUSSION AND CONCLUSIONS

Lean construction and BIM have been considered as two important concepts to create positive changes in the construction industry and along the different phases of construction projects (Sacks et al., 2010). Though, despite the increasing interest in lean and BIM and the numerous efforts to study the synergies between them, the implementation of lean principles jointly with BIM is still overlooked (Likita et al., 2022). Especially in design management (Herrera et al., 2021). Additionally, the levels of lean and BIM adoption are still unknown in different locations around the globe. The current study investigated the levels of lean and BIM adoption in France and the impact of lean-BIM integration on design performance. These objectives were achieved following the analysis of survey results filled by practitioners from different design firms in France.

The analysis of the results showed that BIM is more adopted in the studied firms in comparison to lean. This is unsurprising, especially with the increased interest in BIM due to the recognition of its different benefits and wide implementation around the globe to the limit that it was described as the “biggest change” that happened recently in the AEC industry (Tauriainen et al., 2016). The case for lean is a little bit different. While lean was labeled by some practitioners as the philosophy that can provide “revolutionary” improvements to the AEC sector, its adoption is still facing different barriers among them the lack of awareness and knowledge about it (Albalkhy et al., 2021; Albalkhy & Sweis, 2021). Additionally, for years, BIM has been a mandatory requirement in the construction sector in many countries (Bolpagni et al., 2017; Tranchant et al., 2017), which is not the case of lean despite the different calls and initiatives to increase its adoption.

Despite the greater adoption of BIM, the results of the study showed that it has not delivered its full potential and is not regularly practiced for different purposes in French design firms. More specifically, the results showed that some companies still do not adopt BIM, and others started its adoption less than a year ago. These results are consistent with another study conducted in 2017 about BIM adoption in 206 Small and Medium-Sized companies (SMEs) from the French construction industry that showed BIM adoption was not very high despite increasing (Tranchant et al., 2017). The same study reported complicatedness in the transition toward BIM by the surveyed companies and felt that BIM would not present improvements in terms of cost and time savings for the companies. This might be an explanation for the absence of the full implementation of BIM in the studied firms in this study. Another explanation might be that BIM is not yet a mandatory practice in France.

Concerning lean adoption, the results of the study are consistent with some claims in the literature that lean is not fully or routinely adopted in France (Chaize et al., 2022; Dakhli & Lafhaj, 2017). Nevertheless, due to the lack of studies about the challenges facing lean adoption in France, it is difficult to define the exact reasons behind this result. However, the lack of training on lean in the vast majority of the studied firms might indicate the presence of two serious barriers to adopting lean, which are the lack of support from top management and the lack of skills and knowledge (Albalkhy & Sweis, 2021).

Despite the lack of full implementation or adoption of lean, the current study investigated the presence of some lean tools, as in some cases, these tools might be implemented but without a full adoption of lean. The results showed that co-location or big room and A3 problem-solving are the most adopted tools. This might show some orientation toward collaboration to find solutions for design problems and improve the design. However, the implementation of these tools is only found in around 25% of the companies and there is no evidence that these tools are implemented routinely or perfectly. The lack of lean implementation in the design may cause losses of opportunities to improve trust, communication, collaboration, cost saving, and on-time delivery of the design (Chaize et al., 2022; Khan & Tzortzopoulos, 2015).

Despite the absence of full BIM and lean adoption, the results of the study showed some promising, but not full, results regarding the use of lean-BIM integration in design management. This was due to the acceptable evaluation for the overall lean-BIM integration (mean= 3.73 out of 5.00). This may show the opportunity to benefit from both concepts even if they are not fully adopted to improve the design. The results show that the client value is the most appreciated dimension while considering lean-BIM integration. While studying the design performance, similar results were found as the highest evaluation was for client satisfaction, understanding of the client's needs and requirements, and ability to cope with the changes. This may show an achievement of one of the principles of lean, which is the focus on the client (Albalkhy & Sweis, 2022). However, collaboration is still not enough; may be due to the contracting methods.

Studying the impact of lean-BIM integration showed that the latter significantly affects design performance. This is consistent with many studies in the literature that showed that lean and BIM together can work together to improve design deliverables, achieve higher client satisfaction, improve the quality of the design, and avoid delays (Bolpagni et al., 2017; Herrera et al., 2021; Tauriainen et al., 2016). Nevertheless, due to the small sample size in the study, this result needs to be validated in further investigations and with larger and different samples from different locations around the globe.

The small sample size is one of the limitations of this study, which hinders the full understanding of the overall evaluation of the studied variables. Future work with larger samples is recommended. Additionally, while this study uses the survey to achieve its objectives, further investigations can be conducted using other data collection methods such as interviews and case studies. Finally, while the survey included questions about the adoption of lean tools, further investigations based on the assessment of maturity levels with these tools might be conducted.

The current study aims to provide an understanding of the current situation in terms of lean-BIM integration in France. The results of this study are helpful to provide insights into the needs for these concepts. While lean-BIM integration was found to affect the design performance, this result might be helpful to achieve better design outcomes due to the adoption of lean and BIM. For researchers, the current study tries to fill the gap concerning the limited resources for the joint implementation of lean and BIM, especially in the design phase. The used tool in this study might be applicable in other locations.

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LEAN AND INDUSTRY 4.0 IN BRICK MANUFACTURING: A DIGITAL TWIN-BASED VALUE STREAM MAPPING PROPOSED FRAMEWORK

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ABSTRACT

As one of the most important industries to face the global housing challenges, brick manufacturing can benefit from the principles of lean and the applications of Industry 4.0 to achieve better organizational, environmental, and operational performance. This study reviews the efforts made on lean-Industry 4.0 integration in brick manufacturing and proposes a framework to support this integration. The proposed framework is based on the use of digital twin (DT) technology to create dynamic and automated Value Stream Mapping (VSM). The proposed framework aims to continuously visualize, monitor, and improve the flow, value creation, and waste elimination in brick production processes. The study also reports the state of the implementation of the framework in a brick company in France as a case study. Validating and testing the framework is possible in different types of manufacturing companies; even out of the brick manufacturing sector.

KEYWORDS

Brick manufacturing, Lean, Industry 4.0, Digital twin (DT), Value stream mapping (VSM), Internet of things (IoT), construction and housing, France.

INTRODUCTION

With roots going back thousands of years ago, brick manufacturing is one of the oldest industries in the world whose products (i.e. bricks) are among the oldest materials used in buildings and remain a basic ingredient in modern construction (Brick Development Association, 2017). Bricks nowadays are used in more than 25% of houses and construction projects (Singh et al., 2021). Therefore, with the exponential global population growth (the global human population increased by one billion people since 2010 to reach 8 billion people in 2022) (United Nations, 2023), brick manufacturing is considered among the most important industries to respond to the increased global housing problems.

Despite its significant role, brick manufacturing is facing numerous challenges. One clear challenge that has received a lot of interest in the last few years is the negative environmental performance of the brick manufacturing process and brick factories. This includes the increased

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energy consumption, pollutants, CO2 emissions, and large amounts of physical waste (Baude et al., 2021). Another important challenge that received less attention is related to the operational performance and the efficiency of the manufacturing processes while maintaining a high-quality final product. This includes efficiency, lack of adequate funding, lack of skills, poor operational performance, and low productivity and effectiveness (Arevalo-Barrera et al., 2019; Chavez et al., 2019; Utami Handayani et al., 2020).

Similar to any industry, and within the era of digitalization, brick manufacturing has the opportunity to benefit from the applications of the fourth industrial revolution; or what is known more now as "Industry 4.0". Additionally, lean, as a philosophy that has shown noticeable improvements in various industries can help the brick-manufacturing industry to find solutions for the problems it encounters (Aka et al., 2019, 2020; Karmaoui et al., 2022). This study proposes a framework to integrate lean and industry 4.0 in brick manufacturing. The framework was proposed based on studying the case of a French brick factory. More specifically, the proposed framework was built using the integration of digital twin technology to improve the results developed when using the known lean tool; value stream mapping (VSM).

LITERATURE REVIEW

LEAN

The philosophy of lean originated in Japan following the development of the Toyota Production System (TPS). Since the beginning of publications about this philosophy, lean has been understood based on different principles including the identification of value based on the client's needs and requirements, value stream mapping and waste elimination to achieve a better flow of materials and information, establishing pull and producing only what is needed, achieving continuous improvement, and respect for partners and people (Liker, 2004; Womack & Jones, 1996).

With these principles, various lean tools have been presented to improve quality, value generation, resource efficiency, reduction of the environmental impacts of waste, and productivity gains (Hines et al., 2023). Examples of these tools include Just-In-Time (JIT), Value Stream Mapping (VSM), error proofing (Poka-Yoke), Kanban, and others (Valamede & Akkari, 2020). The presentation of these tools in the manufacturing sector, and then in other sectors such as the medical and construction sectors, showed remarkable results regarding quality improvement, cost reduction, time saving, safety conditions, and environmental performance (Albalkhy et al., 2021).

The used tool in this study is the VSM, which is a 2-D map that visualize all the actions in the production line and covers adding-value and non-adding-value activities. Via this 2D visualization of the flow, VSM helps to eliminate waste, streamline work tasks, reduce lead time and costs, and increase productivity quality (Valamede & Akkari, 2020).

INDUSTRY 4.0

Over history, energy sources and disruption in production have been the main reason for moving toward new revolutionary actions in production systems (Dakhli & Lafhaj, 2018; Valamede & Akkari, 2020). These actions started with the mechanization efforts that resulted in the emergence of the steam engine, by which, the first industrial revolution started. The second industrial revolution happened following the increased use of electricity and introduced the principles of mass production. Then, with the development of computerized systems, an automation-based era started as the third revolution. The fourth industrial revolution appeared in 2011 and aimed to apply the principles of robotization, cyber-physical systems (CPS), the internet, smart-oriented technologies, and application in human-machine interaction systems (Hines et al., 2023).

Understanding Industry 4.0 can either be based on the purposes of the application of the new smart technologies or based on the used technologies (Hines et al., 2023). An example of the first classification was that proposed by Tortorella et al (2022), who classified Industry 4.0 into six use categories: "interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity". An example of the technology-based classification was raised by Pagliosa et al (2021) and included the Internet of Things (IoT), Cyber-Physical Systems (CPSs), cloud computing, big data, Digital Twin (DT), Virtual and Augmented Reality (VR and AR), 3D Printing, simulation, and others.

The main used technology in this study is the DT, which can be defined as *"a living model of the physical asset or system, which continually adapts to operational changes based on the collected online data, information, and can forecast the future of the corresponding physical counterpart"* (Qi & Tao, 2018).

LEAN AND INDUSTRY 4.0

The last few years have witnessed several calls to integrate lean and industry 4.0 practices (Hines et al., 2023; Ramadan et al., 2020; Rosin et al., 2020; Sanders et al., 2016; Santos et al., 2021). In some of these calls, lean was considered one of the new principles of industry 4.0 due to the shared objectives with industry 4.0 concerning value creation, modularity, visualization, and service orientation (Albalkhy et al., 2021).

Supporters of the lean-Industry 4.0 integration believe that with the rapid technological advancement, lean alone is not enough, and at the same time, Industry 4.0 alone is not enough as well (Hines et al., 2023; Santos et al., 2021). While Industry 4.0 helps achieve changes in the business model, social level, and technological levels due to the integration of real-time data that can help improve decentralization and rapidness of the decision-making process, it still needs to be integrated with lean to support creating changes on the managerial and organizational level (Santos et al., 2021). Additionally, despite the changes in nature between lean as a low-tech approach that supports standardization and simplicity, and Industry 4.0 as a high-tech that calls for innovation, there are rooms to benefit from their integration and creation of a better flexible system that ensures the rapid reaction to market changes, provide a higher quality of products, and achieve higher customer satisfaction (Hines et al., 2023; Santos et al., 2021).

In their study that was based on the perspectives of 87 academic experts in the field of lean and Industry 4.0, Hines et al (2023) defines lean Industry 4.0 as: *"An innovative socio-technical paradigm that uses both human and artificial intelligence and relies on the strategic, cultural, systems, and tools of Lean as well as the various Industry 4.0 digital technologies continually and discontinuously used to improve both single organizations and their supply chains with a focus on simplifying and managing complexity to benefit the triple bottom line and hence meet specific customer and organizational needs as well as the expectations of employees and wider society".*

LEAN AND INDUSTRY 4.0 IN BRICK MANUFACTURING

Brick manufacturing is characterized as a small-medium enterprises (SMEs)-based industry (Kumar & Sharma, 2021). This type of enterprise has many opportunities to benefit from the adoption of lean Industry 4.0 such as cost reduction, faster growth, and flexibility increase (Elhusseiny & Crispim, 2022). Nevertheless, many barriers hinder this adoption in SMEs. Among them, the lack of financial capabilities, lack of information communication technology (ICT) infrastructure, lack of managerial flexibility and support, fear of change, lack of knowledge, and lack of skilled employees (Agostini & Nosella, 2020; Albalkhy et al., 2021; Albalkhy & Sweis, 2021; Elhusseiny & Crispim, 2022; Kolla et al., 2019). In addition, according to Kolla et al (2019), most of the lean Industry 4.0 frameworks and models are too complex and do not fit the nature of SMEs.

All these barriers might explain the lack of sufficient studies about lean Industry 4.0 adoption in brick manufacturing. During the conduction of the literature review, a limited number of studies were found about both topics. The aims of these studies were the identification and removal of lean wastes in brick manufacturing processes (Aka et al., 2019, 2020; Arevalo-Barrera et al., 2019), identification of possible actions for quality improvement (Cabrera & Oliveros, 2017; Carrero et al., 2021), and design of status analysis system for brick machines using IoT (Xu et al., 2020). This study aims to contribute to the existing literature and propose a lean Industry 4.0 framework that is developed to fit the requirements and nature of brick factories.

RESEARCH METHODS AND PROPOSED FRAMEWORK

The research adopts the case study as the methodology as this approach that is used to generate an in-depth, multi-faceted understanding of a complex issue in its real-life context. The proposed framework followed the conduction of different field investigations in a brick manufacturing factory (will be explained in the case description below).

The proposed framework is based on the use of green-digitalized VSM. The use of VSM provides opportunities to identify production wastes and achieve improvement in the process. VSM can be linked with environmental metrics to identify the existing problems that affect environmental performance (Nguyen & Sharmak, 2022). Normally, VSM is applied on levels; starting with the current VSM, which shows the current situation and the existing bottlenecks and wastes in the process, then the future VSM, which aims to integrate changes in the process to provide improvements and waste elimination, and then, the frequent (normally yearly) VSM that aims to evaluate the progress based on the recommendations of the future VSM. Nevertheless, many SMEs face difficulties in VSM implementation. These difficulties are a result of the reluctance to continuously invest in VSM as a static tool that requires continuous updates (Lu et al., 2021). Therefore, the proposed framework aims to benefit from the advancement of DT and IoT to improve the implementation of VSM.

The selection of DT and IoT was firstly due to their ability to deliver real-time information and connectivity that help achieve continuous monitoring and rapid decision-making to make improvements and optimizations in energy consumption, materials management, process management, and safety (Dardouri et al., 2022; Karmaoui et al., 2022; Lu et al., 2021). The second reason was due to the flexibility of DT systems that can facilitate the application of lean thinking due to the ability to monitor the flow, eliminate waste, and provide visual and real-time access to the management and teams to ensure the continuous improvement and error proofing in the process (Barkokebas et al., 2022; Lu et al., 2021). The third reason was due to the business need of the studied company to deploy DT; similar to what was described by Agrawal et al (2022) as the implementation of DT as a “need pull”.

As shown in Figure 1, the proposed framework is based on two main phases:

- The first phase covers the identification of bottlenecks and wastes in the process. This is based on the use of different data collection methods such as interviews with workers or management staff, surveys, or observations, in addition to the possibility of the use of different types of sensors to collect data about workflow, temperature, humidity, and others. In this phase the current production process can be translated into current VSM using different measures such as cycle time (C/T), change over time (C/O), machine time (M/T), processing time (P/T), and others. Benefiting from the IoT, measures like energy consumption and CO_2 emissions are also possible to be integrated into the VSM. The first phase results in building the virtual model using simulation or software.

- Building the virtual model helps to create a flow of data from the physical model (the production process) to the virtual model. The latter is responsible for processing the data to produce useful information to improve production control and automate decision-making (Agrawal et al., 2022). By making this connection between the physical and virtual models, frequent testing and integration for scenarios and improvements are possible. In this phase, and using the bidirectional data flow between the physical and virtual models, the development of VSM and the monitoring of the production line are done continuously. It is worth mentioning that the second phase is not implemented once. It is continuously implemented aiming at achieving the principle of continuous improvement.

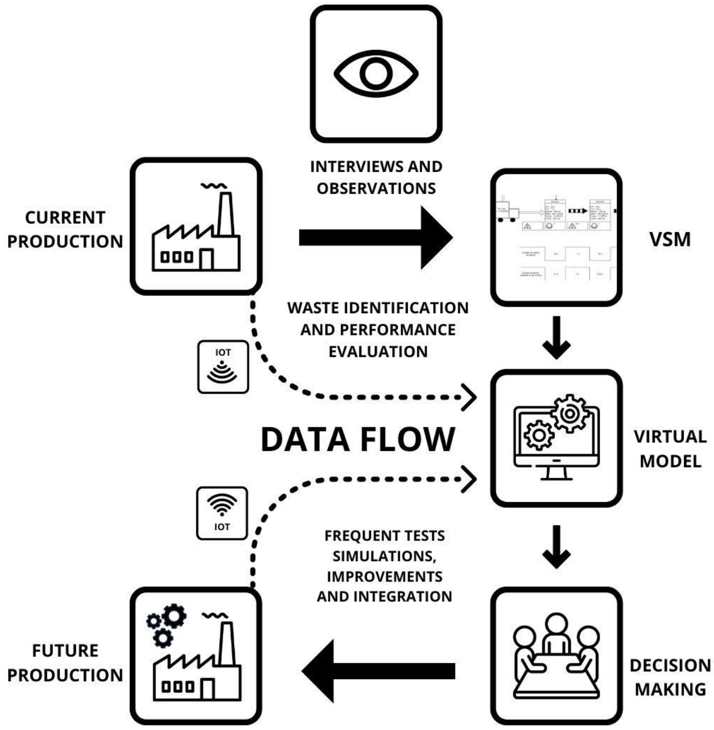


Figure 1: The proposed DT-based VSM framework.

CASE STUDY

CASE DESCRIPTION

Applying the proposed model started in a brick manufacturing company in the North of France. The company, which is a family-based company more than 100 years old and produces different types of clay-based bricks (solid bricks, perforated bricks, and clay brick plates) is a provider of bricks for many projects in France, England, Ireland, and many other locations. Nevertheless, the company faced several challenges during the last few years.

Similar to any company in France, the second largest producer of tiles and brick in Europe (Carole Fossey & Massieu, 2020), the company is experiencing instability in production and an increase in materials prices due to the fluctuated demand due to the impact of the recent war in Ukraine and the pandemic of COVID-19. In addition to the need to deal with the negative environmental and operational performance that results from the levels of pollutants and energy consumption, low machine performance, efficiency rates, strong competition, and skills shortage. Accordingly, to overcome these challenges, the company wanted to adopt lean and industry 4.0 practices to create a flexible, zero-waste, and efficient production line. This paper reports one of the actions taken in this regard.

PROCESS

The process of brick manufacturing in the studied case is shown in Figure 2. In this process, clay is extracted and transported to the production sites and then stored in a warehouse for an average of four weeks. The production starts with the preparation of the brick mixture from the extracted earth and the other raw materials, in particular sand and water. It is first put into dosing devices and then sent to the grinding mill to make the mixture more homogeneous. The material is then conveyed, using a conveyor belt, to a second, more massive aerial dosing unit which mixes a second time and distributes the clay uniformly. Once the mixture reaches the mixer, additional products are added, such as iron oxide and colorants, to give the brick the desired color. The mixture then passes through the extruder, which shreds the clay and compacts it under a vacuum. The strand is then cut with metal wires. After shaping the brick becomes wet and requires drying to remove surface water and reduce its humidity. The firing stage is done in a tunnel kiln that runs on natural gas, with burners and gas injectors. The quality control work is done by hand when the robot unstacks the wagon, so the pace has to be a little slower to give the employees time to spot any non-conforming bricks; stains, cracks, and damaged faces.

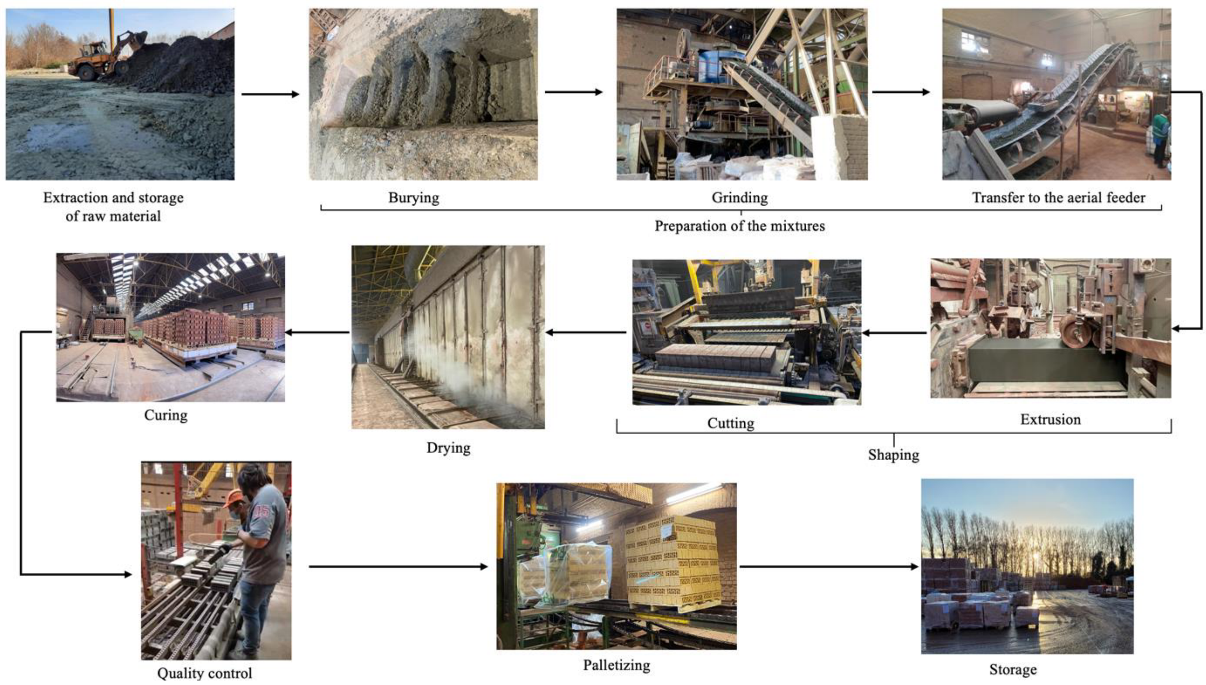


Figure 2: Clay-based brick manufacturing process.

CURRENT VSM AND ENCOUNTERED BOTTLENECKS

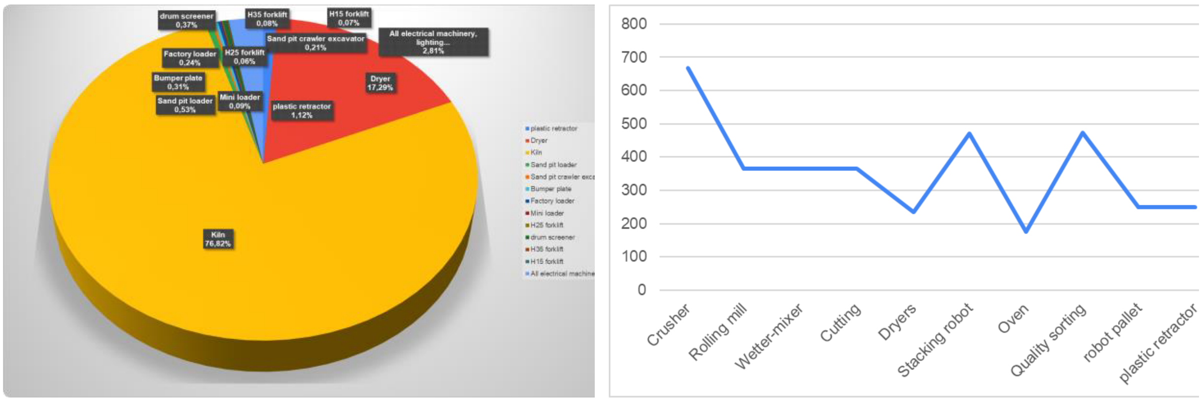
The current VSM was developed following studying the production line. The study covered the red bricks in this phase. Studying the production line was based on a set of observations to identify the different value adding and non-value adding activities and identifying the different phases of production. During these observations, the average time of each phase and at each machine and the bottlenecks in the flow were identified. To confirm the results of the observations with the real situation, the developed VSM was validated through conducting interviews with workers and management staff. Based on the VSM, the total time of non-value-adding activities is 35.5 hours, constituting around 28.4% of the total time in the production process (starting with the arrival of the raw materials and ending with arrival to the storage area). Nevertheless, the efficiency is not optimal as the time spent in the kiln (72 hours) was considered a value-adding activity. This means that neglecting the time needed in the kiln, the percentage of waste in time can reach 67% of the overall process time. In addition to the visualization of the production process and identification of the wasted time, the use of VSM was also helpful to identify the current flow rates, consumed energy, and CO2 emissions in each machine in the process (as shown in Figure 3). This helped to identify the bottlenecks and problems in the process, which can be summarized in:

1) High levels of energy consumption and CO2 emissions in the kiln (the kiln is responsible for more than 75% of CO2 emissions and more than 70% of energy consumption).

2) High levels of defects in different places along the process including for instance defects resulting from bricks falling after getting out from the kiln due to wrong positioning and bricks due to instability of the old wagons.

3) Stoppages in the production line due to some reasons such as fallen bricks in the wagon path, problems in machines, and stoppages due to the cutting machine. The latter is responsible for a lot of stoppages (5-6 times per day) due to frequent failures in the cutting wires, which require their replacement.

4) Levels work-in-progress (WIP), which affects the freedom of movement and creates problems in brick storage.



CO2 emissions per machine | Flow rate in each machine (Kg/min)

Figure 3: Used metrics in the current VSM.

Accordingly, the proposed solutions include:

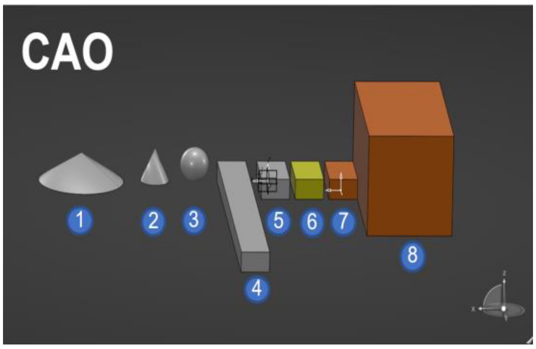
1) Continuity of the process monitoring to identify the reasons for the wastes in the production process.
2) Apply lean principles and tools such as pull, Just-In-Time (JIT), 5S, and supermarket to eliminate wastes and reduce levels of WIP.
3) Use of IoT to provide alerts when stoppages in the production line happen.
4) Conduct numerical simulations and study the different placement of the bricks in the kiln (so that the heat reaches the brick in the middle of the bottom car faster) which will reduce the firing temperature and the firing time. As a result, trying to improve efficiency and reduce energy consumption and CO2 emissions.
5) Implement predictive maintenance to predict future failures in machines and avoid machines breakdown that would cost productivity loss.

BUILDING DT MODEL AND FUTURE DIRECTIONS

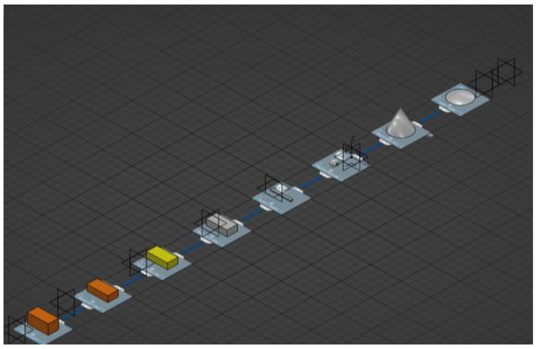
Despite the role that VSM played in identifying problems in the production process, some limitations require the use of more dynamic and digitalized VSM. Firstly, the current VSM is static; therefore, with the stoppages in the production line, its results need to be updated frequently. Secondly, the current VSM was done for only one product in the factory. To apply the principle of leveling (i.e. Heijunka), there is a need for a flexible system that can integrate more than one product; such improvement can be done using DT as stated by Lu (2021). Thirdly, due to the changes in the production line (affected by the stoppages and unexpected events), it is not easy to identify improvements in efficiency and WIP reduction; especially with the presence of workers turnover (Lu et al., 2021), which happens in the studied case. Finally, the use of an interactive model that links the physical process and the digitalized process can provide real-time data and updates about the effectiveness of the changes in the production process (e.g. due to repositioning of bricks in the kiln, changes of current wagons, and predictive maintenance implementation).

Therefore, the work started to build the digital twin model. So far, the team was able to build the 3D model and distribute a set of needed sensors linked with the IoT platform. The 3D model was built using "The 3DEXPERIENCE platform from Dassault Systèmes". The current work covers:

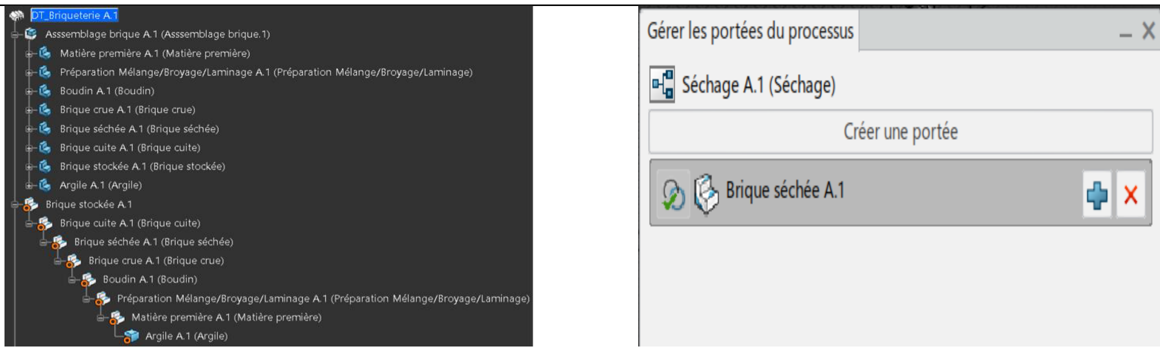
- Building the 3D design and modeling the brick in its different states (as shown in Figure 4-a). Each transformation of the brick corresponds to a visual of the brick, starting with the extracted earth, then the preparation of the earth, the molded, cut, dried, baked, and stored brick
- Building the Manufacturing Bill of Materials (MBOM) (Figure 4-b), which integrates the different 3D models of the brick in the logical order of the manufacturing process.
- Process planning and flow simulation (Figures 4-c), which covers creating workstations consistently with the flow in the original process and linking them to the two previous phases. This step also covers the creation of the workstations, which is a critical step as it allows the definition of the different workstations, the production line as well as the time that the brick spends at this station. In this step, several parameters are defined such as throughput, cycle time, estimated operation time, and the interval between failures and repair time.
- Scenarios testing and monitoring (Figure 4-d): as a result, the digital twin system, presents useful information in the shape of a Gantt Chart about the systems, operation, parts, and resources. The most important criterion is the utilization rate of the systems/machines. This enables checking how the systems are used in the production line, and if a change is made, observing the repercussions on the other systems, especially the storage areas, and checking if this affects the production downstream. An example of the testing of different scenarios was predicting the stoppages of the cutting machine, which as mentioned above, was one of the identified bottlenecks that affect the flow in the process based on the results from the VSM. The machine is made of steel wires that allow cutting the raw brick. However, the process must be stopped manually when the wires break. This leads to other problems that increase the workload and impact the productivity of the company. The digital twin can predict the breakage of a wire and automatically stop the process. For this, it is necessary to implement sensors on the machine (a noise sensor (a microphone), force, and proximity). Thus, the implementation of sensors and alarming system to provide alerts when the machine stopped.
- Building sensors network and connecting the IoT platform with the developed virtual model: to ensure the bidirectional flow of data between the virtual model and physical model, a network of sensors is currently under construction to be connected with the developed virtual model. A complete digital twin should make it possible to monitor the work for each machine of the brick factory and to show their impact on the production line in the event of a problem or modification. Therefore, the built network aims to cover all the production phases and machines that were covered in the virtual model.



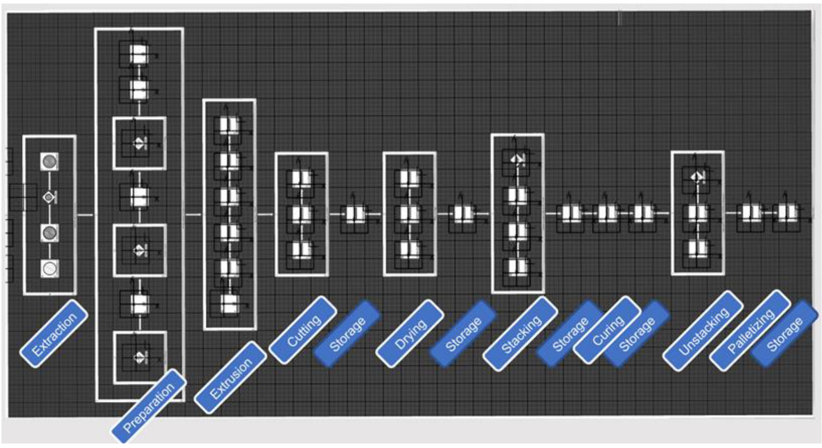
(a) Modeling different states of the brick



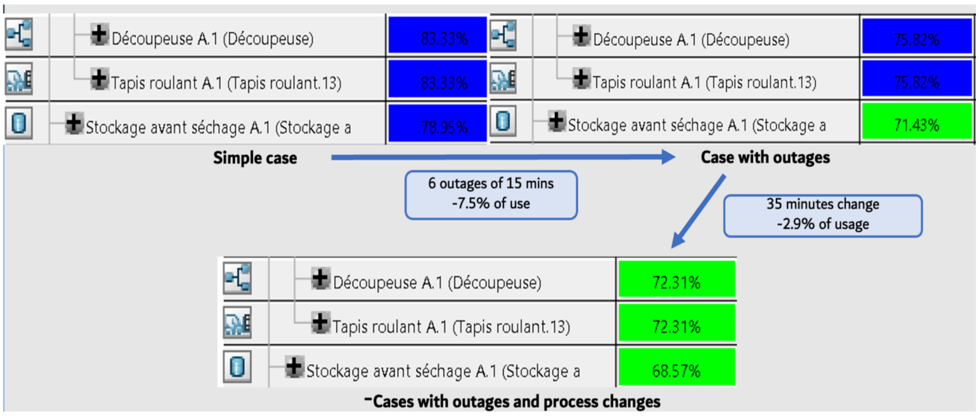
(b) MBOM



(c) Process planning and flow simulation.



(d) Modeling of the production line



(e) Example of scenario testing

Figure 4: Building the DT model.

DISCUSSION AND CONCLUSIONS

The current study proposed a framework that is based on the integration of lean and Industry 4.0 to improve production performance in brick manufacturing. The proposed framework is based on the use of VSM and digital twin. While the former is well recognized in visualizing and improving flow in manufacturing processes, the latter serves as a supporting tool that aims to maximize the benefits of process mapping. Digital twin is helpful as well in mitigating the impact of the static state of the VSM and continuously providing improvements to the production process. Therefore, the proposed framework goes beyond the use of static tools to visualize the production process and proposes the use of dynamic model that is linked with IoT platform to ensure monitoring the production process, testing different production scenarios, and integrating real-time data to improve predictability, and autonomous and information-based decision-making processes. Additionally, the integrated data from the IoT platform and digital twin is helpful to continuously monitor production and achieve continuous VSM models. As a result, generating greater value for the client, creating stable and smooth flow, and achieving continuous improvement.

The proposed framework is currently implemented in a French brick factory. While the implementation is still in its early phases, the framework has shown some potential to improve predictability, waste elimination, visibility, and decision-making in the factory. Nevertheless, further investigations are needed to validate the framework. Future works can be done based on case studies to modify and test the framework even in other industries. Other research works can investigate the impact of the model on the performance, identify key performance indicators for the framework, or identify the barriers to implementing it.

This study aims to contribute to the ongoing efforts to integrate lean thinking and Industry 4.0 practices aiming at benefiting from the two concepts. In addition, the study serves as a good example of how to improve performance in brick factories in particular and SEMs in general using lean-digitalized models.

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COST REDUCTION IN CONSTRUCTION THROUGH PROJECT COMPATIBILITY IN A VIRTUAL PROTOTYPE

Joseph Hakkinen Alves Santos[1] and Camila Campos Goméz Famá[2]

ABSTRACT

The design stage is decisive for the Product Development Process, as it is in this stage that the main guidelines of the projects are defined, which directly affect costs, deadlines and production methods. In this sense, virtual prototypes have been used to approve project alternatives, perform engineering analysis, support production planning and present the product to customers. Thus, they allow the reduction of time and resources in decision-making, in addition to predicting problems that may lead to difficulties in execution. In this context, the research sought to optimize pre-existing projects of a popular standard residence through the development of a virtual prototype through the Autodesk Revit tool where it was possible to reconcile the structural, electrical, hydraulic and architectural projects, in addition to adapting such projects with the construction techniques used by the construction company. In this interactive process, the automatic method of detection of interferences (crash-detection) and the manual were applied, through the contribution of the stakeholders of the work. The estimated direct savings obtained per house built was around BRL 905.00, knowing that this development was a housing complex of 90 houses, a reduction of approximately BRL 81 thousand reais was obtained in total.

KEYWORDS

Lean construction, prototype, BIM.

INTRODUCTION

The building construction process is characterized by a high level of variability, which negatively impacts its performance in terms of time and cost (Cruz et al., 2018). Although the construction industry has made changes and improvements in recent years, there is still a need for changes in both production and product development processes and management processes, since it is still far from being equated to the levels of productivity, quality and efficiency of other industries (Navon and Sacks, 2007, Heigermoser et al., 2019).

Project management during the construction period requires contractors to deal with many uncertain and complex tasks that, in highly interrelated networks of activities carried out by multiple stakeholders, can lead to a tendency to deviate from schedule (Sarhan & Fox, 2012).

Such problems of uncertainty in the production process may occur due to lack of better knowledge of working methods (Howell and Ballard, 1999) as well as design errors and incompatibility of what is planned and really necessary (Li et al., 2008).

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Waly and Thabet (2002) emphasize that these errors and mistakes in the construction planning schedule occur frequently, since their compilation depends largely on the limited knowledge and experience of the project team.

Due to this complexity and the large number of factors involved, Li et al. (2009) says that a major limitation for many projects is the lack of effective computer-aided technology for resource allocation and planning. Therefore, this can be an efficient tool to help project planners.

In this sense, even though it is still considered an industry that is not technologically advanced, scholars have studied topics such as waste reduction, process improvement and virtual information flow in recent decades (Landim et al., 2022).

Given the scenario presented, Bayhan et al (2021) argue that companies that seek to improve their production processes should invest primarily in Lean and BIM, with the aim of reducing waste, such as rework, loss of time and costs.

As stated by Dave et al (2011), there are two categories of problems related to construction: a) problems in the execution of construction processes; and b) problems in product representation. While Lean Construction offers an efficient way to solve issues related to construction processes, BIM helps to solve many problems related to projects (products), providing visualization tools and intelligent models of products based on a virtual platform. BIM functionalities are compatible with Lean Principles and vice versa, providing a synergistic effect.

Because of that, the relation between BIM and Lean have been more developed and different authors have studied the relation between BIM and Lean, identifying positive interactions in their combined use (Hamdi & Leite, 2012; Mandujano, Alarcón, Kunz, & Mourgues, 2016; Sacks et al., 2010).

Lean is a production philosophy that focuses on customer needs, production flow and continuous learning (Huntzinger, 2002). In the construction industry, the lean philosophy has been applied for decades, and due to the special features of the construction industry in relation to factory production, the construction industry has developed its own applications of lean production and lean design.

Building information modeling (BIM) has been recognized as a leading innovation in the construction industry worldwide to improve the productivity capability in this segment (Husain, Razali and Eli, 2018) and can potentially be used with human input to store and structure customer requirements and connect this information to building models to visualize requirements, keep them up-to-date, and perform project evaluation tasks (Jansson, Schade and Olofsson, 2013).

Currently, BIM is one of the most important current approaches to address productivity problems in the construction industry, with an increasing adoption rate in the last years (Peralta and Mourgues, 2022). This high interest can be explained by BIM´s promise of improving the construction performance and efficiency (Azhar, 2011). BIM enables error detection, omissions, and clashes beforehand, which helps reduce waste and makes construction processes more linear (Eldeep et al., 2022).

Crotty (2012) points out that the use of BIM, in addition to enabling the improvement of the quality of project information, the tool also allows establishing mechanisms and procedures for how information is communicated and shared among members of a team.

MacLeamy (2004) also suggests that BIM implementation effort from the early stages of the project causes cost savings with late changes in the product lifecycle. Nevertheless, if BIM is not properly implemented, organizations may incur in additional costs or reductions in efficiency (Chu, Matthews, & Love, 2018). One of the causes for these potential unwanted outcomes is stakeholders without the required capabilities and awareness for the BIM uses in the construction projects (Gu, Singh, Taylor, London & Brankovic, 2008).

Thus, this research sought to reduce execution costs due to errors that occurred during the construction of popular standard residential buildings from a case study using a virtual prototype modelled through the Autodesk Revit tool for project compatibility.

LITERATURE REVIEW

In general, wastes in construction are associated with overproduction, transport and processing of materials, defective products, unnecessary movement of workers, lack or excess inventory, among others (Antunes Junior, 1995).

In this context, Lean techniques supports not only the continuous improvement of the production system by avoiding waste, but also the optimization of the interaction between humans and machines (Cisterna et al., 2022). Lean Construction is the adaptation of Lean principles derived from the Toyota Production System into the construction sector. (Salem et al., 2006).

Today, the application of Lean techniques to construction (Lean Construction) plays a crucial role on many construction sites as with them processes can be stabilized and continuously improved (Cisterna et al., 2022).

According to Sacks et al. (2020), several physical resources (personnel, equipment and materials) interact in construction workflows, many of which are temporary. In addition, construction projects have required the availability of increasingly detailed status information to find and remove constraints, prepare tasks, staff and perform services. Lean principles provide a solid foundation for dealing with these issues; however, their methods require a considerable flow of information and resources, which are difficult to maintain without the support of information technology.

In addition, the elaboration of the projects also has a great impact on the development of the construction. According to Adesse (2006), projects should be considered as the "backbone" of the production process, since design failures are also responsible for negatively affecting the production process.

According to Muller and Saffaro (2011), among the main design flaws stand out: the lack of compatibility between "the functional parts of the building", the lack of detail of the information and the lack of communication between the designers.

These constant design errors bring to light the need to produce more complex and well-designed projects in order to avoid errors and reduce costs. In this sense, the information technologies implemented in engineering and architecture software, enable designer's three-dimensional virtual models of the product, which was previously taken with two-dimensional representation (Muller and Saffaro, 2011).

In this sense, virtual prototypes are fundamental for error checking and continuous project improvements. For Ulrich and Eppinger (2000), prototype can be considered an approximation of the actual product over one or more dimensions of interest. These models are of the physical or analytical (virtual) type, where analytical models can be considered intangible ones, which use computational software for their modelling. This model enables better and faster ways of modifying design at a low cost (Muller and Saffaro, 2011).

In this sense, the BIM philosophy is able to promote harmonization and integration between the areas of architecture, engineering and construction throughout the production of projects. Thus, this tool has great use in the optimization of multidisciplinary projects, bringing an improvement in the quality of products (Miranda and Salvi, 2019).

BIM enables error detection, omissions, and clashes beforehand, which helps reduce waste and makes construction processes more linear (Eldeep et al., 2022).

METHODOLOGY

The method used in this research was Design Science Research (DSR), a method in which it consists of analyzing from various perspectives the conception and execution of projects. The methodology DSR is a research model oriented towards solutions to practical problems in technology and engineering. The process includes identifying the problem, defining objectives, developing artifacts, demonstrating effectiveness, and evaluating results. The aim is to produce useful knowledge to improve practices and decisions in a specific field.

According to Peffers et al. (2007), the DSR process consists of six steps:

Identification of the problem: this first consists of identifying and justifying the research problem, aiming to develop an artifact that can provide an effective solution. The definition of the problem also helps to motivate the researcher and the public, in addition to allowing the understanding of the reasoning involved;

Objectives: this second stage consists of defining objectives for a solution based on the definition of the problem and knowledge of what is possible and feasible. These objectives can be quantitative or qualitative and must be rationally inferred from the problem specification;

Design and development: this third stage consist of designing and developing the artifact to solve the problem. It is necessary to determine the desired functionality of the artifact and its architecture, and create the actual artifact based on the theory applicable to the solution;

Demonstration: in the fourth step, the use of the artifact to solve the problem in question is defined and demonstrated through experimentation, simulation, case study or proof;

Evaluation: The fifth step involves measuring and evaluating how the artifact supports the solution of the problem, comparing the objectives of the solution with the actual observed results of using the artifact in the demonstration.

To ensure a structured and organized approach to the research project, an organization chart was established. This chart served as a visual representation of the hierarchy of tasks and responsibilities, providing clear guidance on the progress of the project. Figure 1 shows the details of the chart, describing the different steps and their respective descriptions. By using this chart as a reference, the research team was able to stay focused and stay on track throughout the project. Additionally, it helped ensure that all team members were aware of their respective roles and responsibilities, promoting efficiency and collaboration.

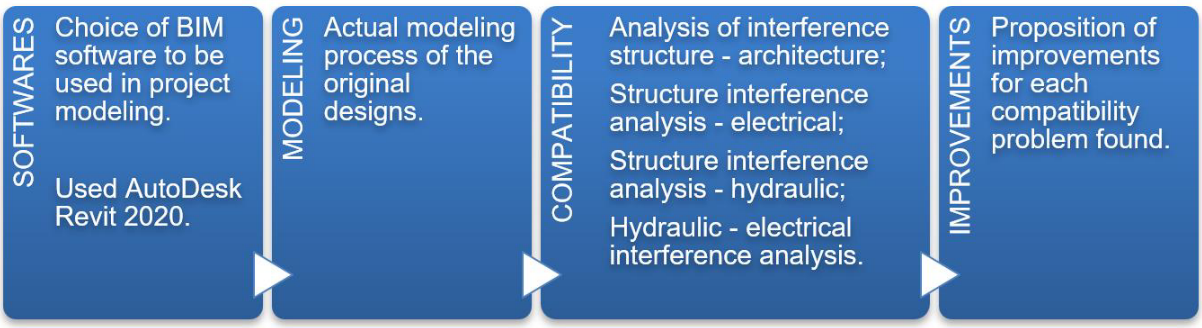

Figure 1: Research organization chart.

Initially, the Autodesk Revit 2020 Educational software was chosen for the modelling of projects, since it had better tools to develop all projects in BIM.

The building in question are houses in the popular standard with 72 m² of built area, replicated in housing estates of multiple units. All the original projects were in the AutoCAD model, BIM modelling started from these projects, according to the architectural plan below (Figure 2).

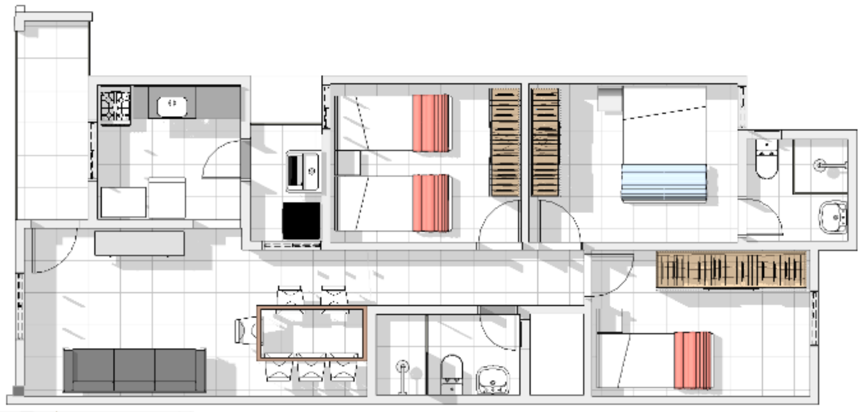

Figure 2: Building layout plan.

After the modelling process of all disciplines, the compatibilizations began. These interactions were done in two ways: manually (based on the authors' experience) and in an automated way (using BIM processes crash-detection). The first structure-architecture analysis aimed to identify differences between the opening spans of doors and windows left in the structural design, when compared to the architect design. This analysis was done manually, verifying point by point of the projects.

The structural-electrical, structural-hydraulic and electrical-hydraulic interactions were made in an automated manner through Revit's own Interference Verification tool. To get to this verification window, we follow the following path:

Collaborate > Coordinate > Interference Verification

Next, the projects that were objectives of identifying interference were selected. In these analyses, we looked for problems of the type contact between structure and electrical or hydraulic elements, or among the elements themselves, which could compromise the execution of the work.

At the end of the interference analysis part, measures of modifications in the projects were proposed in order to optimize the projects as much as possible, reducing costs and facilitating execution.

FINDINGS

From the interactions between structural and architecture, we were able to identify a failure in relation to the dimensions of the doors (Figure 3) and windows (Figure 4).

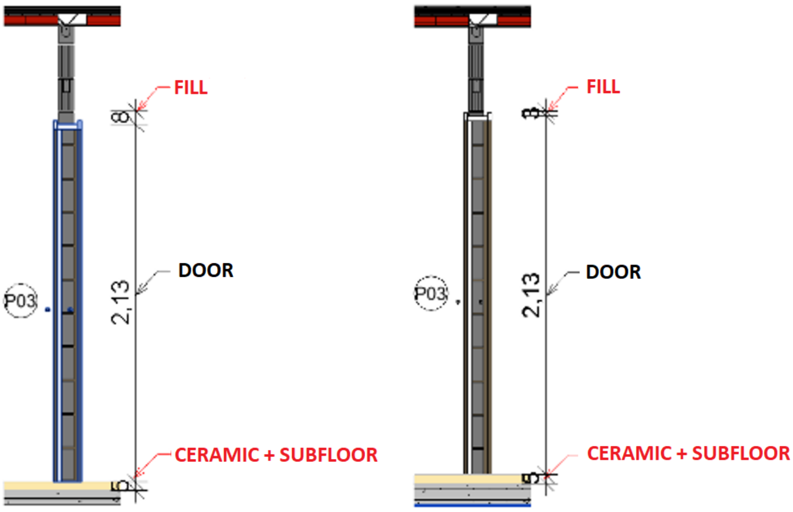

Figure 3: Door before (left) and door after modifications (right).

In the doors, the problem perceived was that: when the floor was executed first, before the structural masonry, the need for a very large filling arose at the top. When this happens, in Brazil, it is common to fill with ceramic bricks, which can generate cracks over time, since this material does not work with the structure. Thus, it was proposed that the floor be executed later than the masonry, thus reducing the upper height of the doors by 5 cm, being now filled only with mortar. This fill was also aligned with the windows.

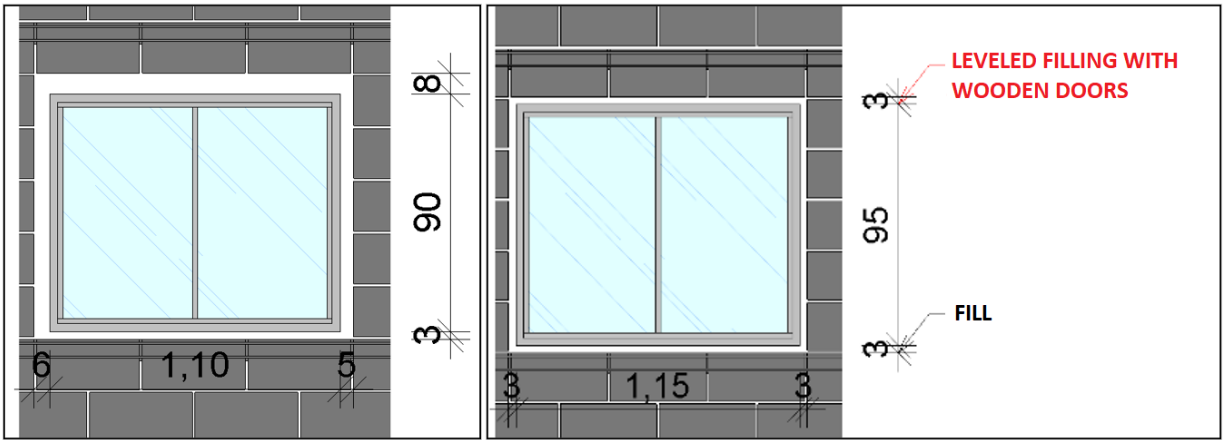

Figure 4: Window before (left) and window after modifications (right).

In this case of the windows, it was identified that they were not aligned with the top of the doors, and for this alignment it would be necessary to increase the frame and leave a mortar fill of 3 cm. Therefore, for the size of the window was increased 5 cm. This problem is related to the modulation of the structure that was made in structural masonry of concrete blocks.

After these modifications, the budget compositions of SINAPI (National System of Survey of Civil Construction Costs and Indexesin Brazil) were applied in order to obtain the final economy of this modification. Each house has 4 windows and 7 doors. The costs obtained after this analysis are shown in Table 1 below.

Table 1: Cost analysis changes in frames

	Windows	Doors
Manpower	BRL 210.00	BRL 370.00
Spared material	BRL 10.00	BRL 10.00
Spent material	- BRL 35.00	- BRL 0.00
TOTAL PER HOUSE	BRL 185.00	BRL 380.00
TOTAL SET 90 HOUSES	BRL 16,650.00	BRL 34,200.00

Another problem identified in this interaction was the lack of alignment between the architecture and the structure. For this, each layer of masonry was modelled, distinguishing the thicknesses of each coating. Thus, it was simpler to align the two projects, and can obtain more trustworthy quantitative (Figure 5).

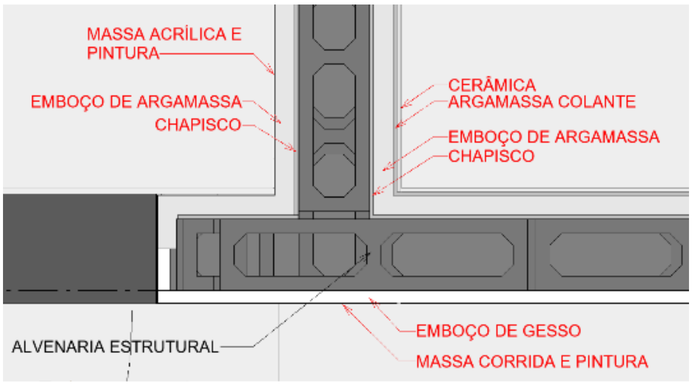

Figure 5: Coating layers of the structure.

Before the electrical-structure interaction, numerous improvements in the project were verified, in agreement with the Brazilian standards in force and the culture of the construction company involved. Figure 6 shows what the project was like before and Figure 7 as the final design resulted after the modifications.

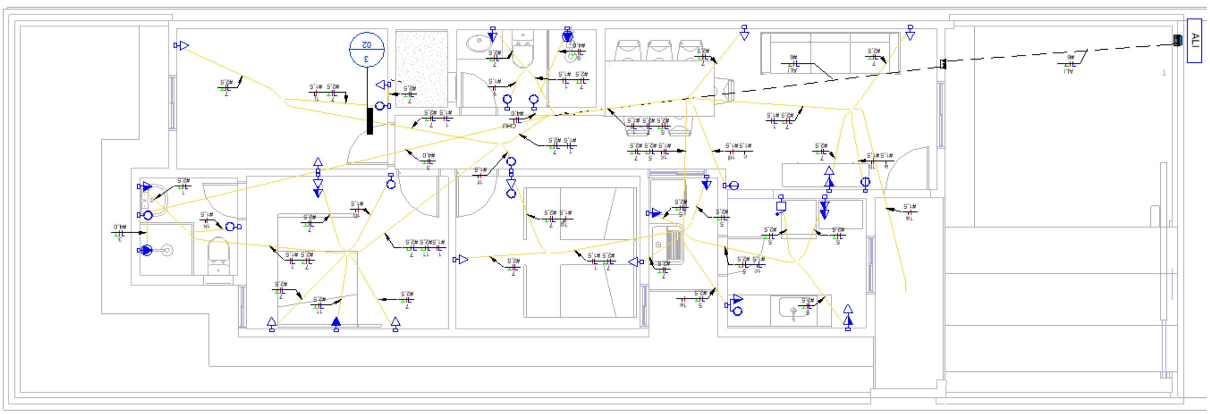

Figure 6: Old electrical design - floor plan. Source: Cipresa, 2018.

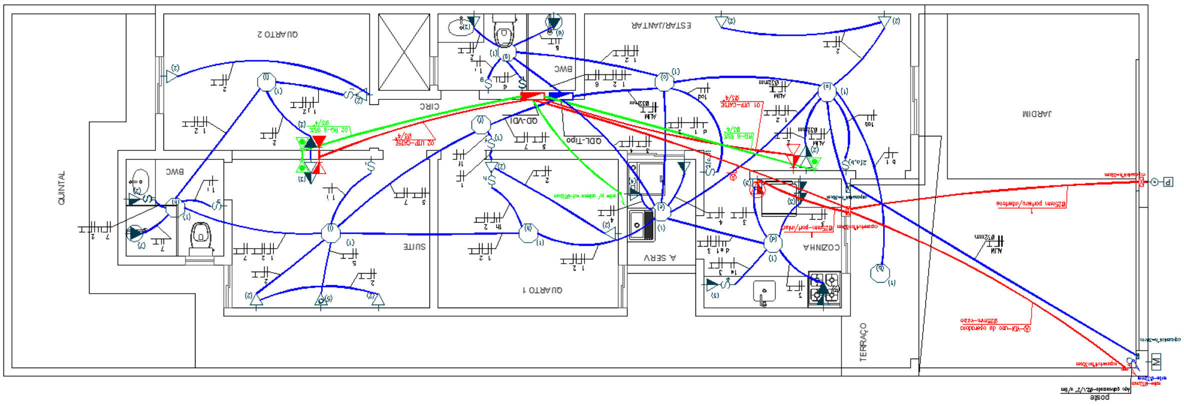

Figure 7: New electrical design - floor plan.

The modifications made in this edition have made the following points:

reduce the route through which the cables passed to power the circuits;

create a separate main power only for the input circuit;

separate the circuit of showers into individual conduits in order to reduce the internal heating of the grouped cables;

create a separate VDI (Virtual Desktop Infrastructure) system with internet input at the front of the residence, and television alimentation by coverage.

By processing the structure-electrical interaction, through crash-detection Revit, it was possible to identify 503 interferences of the structure with the elements of the electrical design. By analysing these interferences, it was possible to see that some 4x2 and 4x4 boxes were not located within the empty blocks. Thus, they were moved to the ideal point as shown in the example in Figure 8.

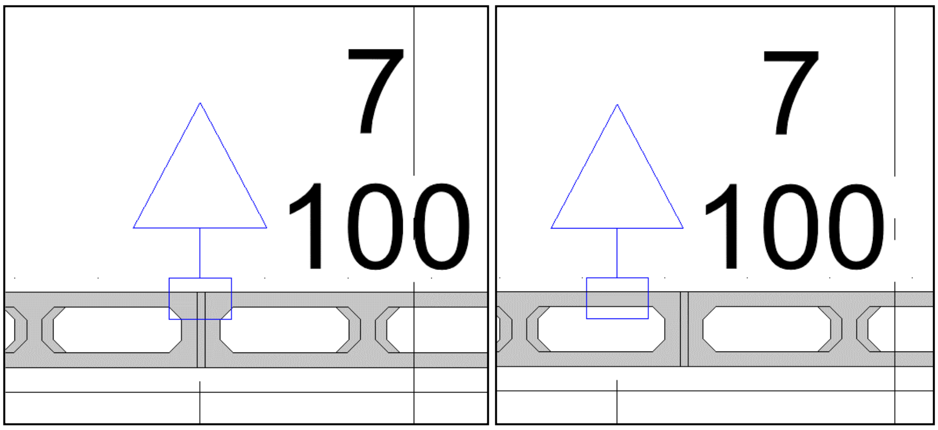

Figure 8: Box 4x2 on the seam of the blocks (left), box repositioned in the empty of the blocks (right).

Other interferences were considered normal, such as conduits passing through the cover slab, since the construction process already uses them in this position.

To verify the costs in this analysis, the fixed amount for labour was used, since the company's culture consisted to pay a single amount per residence to the electrician, and the modifications made would not reduce this service. As for the materials, the base data from SINAPI was also taken for estimated of cost. Based on the modifications made, and comparing the quantity of material before and after, we arrived at the following data (Table 2).

Table 2: Cost analysis changes in electrical design.

	Before	After
Manpower	BRL 900.00	BRL 900.00
Material	BRL 1,800.00	BRL 1,460.00
TOTAL PER HOUSE	BRL 2,700.00	BRL 2,360.00
TOTAL SET 90 HOUSES	BRL 243,000.00	BRL 212,400.00
DIFFERENCE IN VALUES	BRL 30,600.00	

Starting for the hydraulic project, when interacted with the structure, it was possible to identify the pipe connection to structural masonry, which in Brazil is not allowed by the current Norms. In this way, all the pipes were moved out of the masonry. Some connections and pipes were reduced at the request of the builder, so these modifications were not counted as savings due to compatibilizations. The process of compatibilization made it possible to better representation the construction of these elements (Figure 9), so that the gain at execution time becomes almost impossible to quantify.

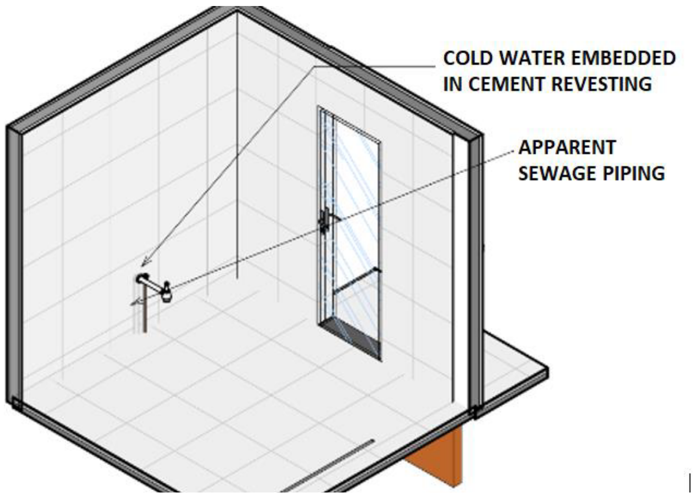

Figure 9: Representation of pipes in the kitchen (example).

The modifications in the hydraulic design were not accounted for, for the reasons mentioned above. Interference analysis was performed between the electrical and hydraulic projects, but no interference was detected. After this step, all representations of all projects were made, now in BIM. These printed and digital projects were made available to the construction team for execution. The 3D visualization of the modelling of this residence can be seen in Figure 10 below.

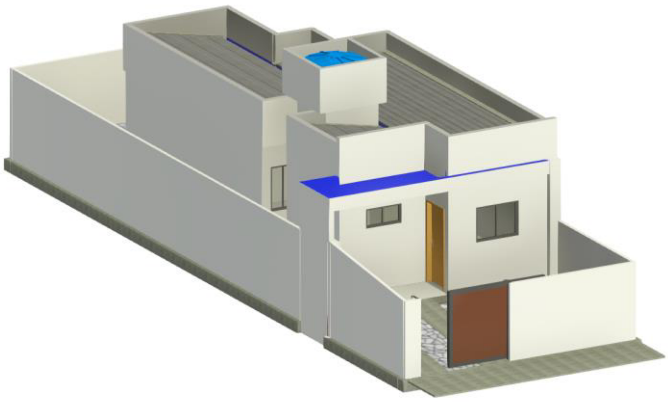

Figure 10: 3D BIM Modelling.

CONCLUSIONS

Modelling in BIM made it possible to explain the construction in a clear and objective way for all the employees involved, bringing with it a rich detailing of information that enabled significant improvements in the old projects of the residences. The joint work of the project team with the construction company's execution team brought greater integration between information, ensuring everyone's participation in the process and reducing future barriers and additional costs at the construction site.

Just relying on automatic compatibility (crash-detection) would not be enough to obtain all the necessary results, since most of the modifications carried out resulted from the construction process. In this way, the active participation of engineers, the master builder and the authors of the paper became essential so that compatibility was carried out properly. Thus, it was possible to ensure that all necessary changes were made and that the final project was completed successfully, without major problems or complications. The integration between professionals and available technologies was essential for the success of the project.

The analysis of the results presented by the BIM modelling process shows the great potential of this methodology to reduce costs in the construction sector. The savings obtained in this specific housing complex of 90 houses represented a final gain of BRL 81,450.00, a significant amount that could be allocated in other areas of the construction. With the implementation of this process, the employees involved were able to obtain greater efficiency and precision in their work, which is essential for the success of any project. It is noteworthy that these savings could be even greater if the project had a larger area or had vertical replication, which reinforces the relevance of this methodology in highly replicable projects.

In addition to the financial benefits, the BIM modelling process also provides significant gains in terms of sustainability and environmental impact. By optimizing the use of resources and reducing waste, the methodology contributes to a more efficient and responsible use of materials, essential for the preservation of the planet. Therefore, the implementation of BIM in construction projects represents not only a financial gain, but also a social and environmental responsibility. This methodology is becoming more and more relevant in the construction sector, and its implementation should be encouraged to promote sustainable development and cost reduction in construction projects.

This type of collaborative approach brings numerous advantages to the construction process, as it allows for the early identification and solution of problems, the elimination of waste and rework, and the maximization of the efficiency of the construction team. In addition, the application of the Lean philosophy in conjunction with BIM technology can result in significant improvements in the quality of the final product, in the reduction of costs and deadlines, and in customer satisfaction.

With this, it is expected that this work can contribute to the dissemination and adoption of more efficient and collaborative practices in civil construction, to the benefit of the entire production chain and, mainly, end users. With the growing demand for more sustainable and efficient construction projects, the Lean philosophy and BIM technology are fundamental tools to achieve these goals, allowing the construction sector to become more competitive and aligned with market trends and demands.

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EVALUATING THE USABILITY OF THE LEANBUILD SOFTWARE APPLICATION AFTER THE DESIGN STAGE

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ABSTRACT

Industries are experiencing a new paradigm shift driven by advanced digitalization, automation, smart technologies, and the internet of things. Lean construction (LC) advocates have been promoting the adoption of existing and emerging technologies through Lean construction 4.0 (LC 4.0). This paper presents an opportunity for the adoption of smart digital technologies in the construction industry in the form of "LeanBuild project management software".

This paper aims to evaluate the usability of the LeanBuild software after the design stage of development. This paper evaluated the ease of use and effectiveness, and assessed the comprehensiveness of the software design flow. Focus groups, questionnaire survey and interviews were conducted with industry practitioners, academics, and software/IT professionals.

The results suggest that the incorporation of data privacy and security, modules for designing and tracking modular and off-site construction, tools for calculating carbon footprints and sustainability, and artificial intelligence, will improve its usability and provide more value to end-users. The paper concludes that while the LeanBuild software has some limitations in terms of scope and functions, it is generally easy to use and effective for its intended users. The study provides insights for software developers to design more user-friendly project management software.

KEYWORDS

Lean construction, digitalisation/technology, project management, software usability test.

INTRODUCTION

Industries are experiencing a new paradigm shift as a result of the rapid growth of technology and its applications, tagged the "4th industrial revolution"; this shift is primarily driven by advanced digitalization, increased automation, smart future-oriented technologies, and the internet of things (Hamzeh et al., 2021). The construction industry is not left out in this socio-

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economic trend of the fourth industrial revolution as it aims to deploy new information and communication technologies (ICT) (Gimenez et al., 2022).

Consequently, the construction industry is facing a restructuring crisis that is based on rethinking and focusing on reforming current production processes and workflows to improve both the production process and the product. The crisis has been facilitated by advances in information technology, which have been promoted as the primary enabler of process reengineering in the construction industry (Gimenez et al., 2022; Love et al., 1996).

There has been a strong advocate for the adoption of existing and emerging technologies as the architecture, engineering, and construction (AEC) sector is yet to fully profit from the established and emerging technologies that characterize the fourth industrial revolution. (Sawhney & Odeh, 2020; Hamzeh et al., 2021, Li et al., 2012). To this end Hamzeh et al., (2021) proposed a change to Lean Construction 4.0 with a focus on maintaining the people-processes-technology synergies between production management theory and digital/smart technology. LC 4.0 is the integration of digital technologies into the construction process (Hamzeh et al., 2021).

Studies have shown a low level of innovation, a lack of collaboration, and limited knowledge sharing in the construction industry (Musa et al., 2019, Alashwal et al., 2011, Ahmed et al., 2017, Xue et al. 2014). The studies noted that investment in Research and development (R&D) and intangible assets (such as new processes) is low (Egan, 1998) due to uncertain demand for new goods, limited collaboration (Musa et al., 2019, Namadi et al., 2017), and low transfer of technology from academia to industry. However, recently, there has been a strong interest to harness the power of innovation through the adoption of digital/smart technologies in LC community. The growth of automated construction is gaining traction as a radical new way of adopting digital tools and technologies

Although many innovative solutions are already being applied on a small scale albeit in few countries, yet the industry still needs large-scale applications or better adaptation of current technological developments. As LC 4.0 advocates for the integration of ICT in the construction industry, it is worth noting that transforming the current construction business model would be difficult without the adoption of innovations, technologies, and techniques by all construction stakeholders. The introduction of new technologies, almost always has an influence, whether favourable or unfavourable. The use of Target Value Delivery (TVD) in many projects throughout the world has had a wide-ranging influence on various parts of those projects (Musa, et al., 2016).

TVD as a Lean practise can serve as a strategic pathway for adopting LC, to eliminate waste and satisfy clients' expectations (Musa, 2019, Musa, & Pasquire, 2020). TVD is an innovation that aims to create value for the stakeholders by reducing waste and ensuring all aspects of the construction process are carried out with the stakeholder's agreed targets in mind; cost, quality, standards, time, and stakeholders' value (Musa, 2019).

This paper presents one of the opportunities for the adoption of smart digital technologies in the construction industry in the form of software, "the LeanBuild project management software." The software aimed to manage various types of projects and is currently being developed and digitized from a framework that emulates TVD principles and values called Framework for Implementing Target Value Delivery (FFITVD). The concept involves the development and deployment of computer software. Presently, the discovery phase of the software development has been concluded. The discovery phase is an important stage in the software development process, during which the goals, objectives, and requirements of the project are identified and defined (Khalimonchuk, 2022). All the necessary software requirements for each project phase, from initiation to closing were considered, and TVD and the traditional construction approach were integrated into the user interface designs. Thus, this necessitate the need to measure the degree of effectiveness and acceptance of the software designs.

RESEARCH GAPS

Despite the growing interest in adopting digital technologies in the construction industry, there is still a lack of large-scale applications or better adaptation of current technological developments. Additionally, while many usability evaluations are conducted at the later stage of the software development process, some researchers have suggested that issues surrounding the ease of use of software should be addressed as early as possible, because such issues are considerably cheaper to rectify early in the development cycle (Hornbæk et al. 2007). However, identifying such issues early is difficult in today's software development practice since usability testing is typically segregated from core software development operations. Lárusdóttir (2011) argued that usability evaluation is essential for ensuring that software applications are effective and easy to use for their intended users and that it should be an integral part of the software development process. Finally, although there is various project management software available currently, many are limited in the area of covering the complete lifecycle of a typical construction project.

AIM AND OBJECTIVES

The paper aims to evaluate the usability of the LeanBuild software application after the design stage of development.

a) To review the literature on current project management software
b) To identify the most common usability problems experienced by users of project management software after the design stage of development.
c) To determine the ease of use and effectiveness of the LeanBuild software application for its intended users after the design stage of development
d) To determine the comprehensiveness of the LeanBuild software design flow

LITERATURE REVIEW

LEAN CONSTRUCTION TO LEAN CONSTRUCTION 4.0

LC is a concept that originated in the manufacturing industry and has been adopted and adapted for use in the construction industry (Koskela, 2000; Musa, 2019; and Daniel, 2017). LC aims to optimize resources, reduce waste, and improve the overall efficiency of construction projects (Musa 2019; Daniel 2017). As an adaptation of Lean production, LC is the application of Lean thinking to the design and production (or delivery, in general) of capital projects (or projects, in general) (Musa 2019).

In construction, the Lean approach has been applied to a wide range of processes, including project design and planning, construction management, and commissioning. Studies have shown that the implementation of LC can lead to significant improvements in the efficiency and quality of construction projects. The development of new digital technologies and the widespread use of the Internet of Things (IoT) has led to the transition from LC to LC 4.0 (Hamzeh et al., 2021). LC 4.0 aims to increase the efficiency and productivity of construction projects while reducing waste and improving quality by leveraging the power of digital technologies. This is achieved by leveraging the data and connectivity provided by digital technologies to better manage the construction process, from design to construction to commissioning and maintenance (Hamzeh et al., 2021).

Some of the major differences between LC and LC 4.0 are the emphasis on data-driven decision-making and the use of digital technologies. LC 4.0 also emphasizes the use of virtual and augmented reality technologies to improve the design and planning processes. This allows for better visualization of the construction process and helps identify potential problems before construction begins.

PROJECT MANAGEMENT AND PROJECT MANAGEMENT SOFTWARE

Project management is the process of planning, organizing, and managing the resources, tasks, and schedules of a project to achieve a specific goal or objective (Project Management Institute, 2017). It involves several activities, including defining the scope and objectives of the project, creating a project plan, identifying and allocating resources, tracking progress and performance, and communicating with stakeholders (Project Management Institute, 2017, Harold, 2017). The goal of project management is to deliver a successful project within the agreed-upon time, budget, and quality constraints (Philpotts, 1996). Effective project management requires the ability to identify and manage risks, as well as the ability to adapt to changing circumstances and requirements (Project Management Institute, 2017). Project management can be aided by the use of tools and software, such as project management software and project management methodologies, such as Agile or Waterfall (Project Management Institute, 2017, Harold, 2017).

Project management software is a digital tool that helps organizations initiate, plan, execute, monitor/control and close projects effectively (Project Management Institute, 2017). There has been a significant increase in the use of project management software in recent years, as it provides numerous benefits over traditional methods of project management. The most common features of current project management software include task management, time tracking, resource allocation, collaboration, project planning, and project reporting (Hoban, 2023). These features help project managers to break down complex projects into manageable tasks, allocate resources and time, communicate effectively with project stakeholders, and track project progress.

However, the current project management software market is highly competitive, and there are a large number of options available, each with different strengths and weaknesses. Choosing the right project management software can be a challenge, and it is important for organizations to carefully consider their specific needs and requirements. As project management software continues to evolve, it will likely become an increasingly essential tool for organizations looking to improve project outcomes. Several challenges have been identified with current project management software, including complexity, limited scope, limited customization, lack of integration, limited access, and concerns about data security and privacy (Goncalves, 2018). The LeanBuild software, which is currently under development, seeking to address these challenges. Despite the availability and implementation of various new and innovative construction technologies, including software, over the past four decades, the construction industry has made slow progress in improving efficiency, due to limited adoption of new technologies among other reasons (Li et al., 2012, McKinsey & Company, 2020).

USABILITY TESTING

Software usability evaluation is the process of evaluating the ease of use and effectiveness of a software application by testing it with a representative sample of users (Lárusdóttir 2011, Dillon 2015, Bruun and Stage 2015). It is an important aspect of software development because it helps ensure that the software is effective and easy to use for its intended users. There are a variety of tools and techniques that can be used to evaluate software functionality and identify opportunities for improvement. These include:

a. Usability testing: This is a method in which users are observed as they complete tasks with the software and data is collected on their performance. This can help identify problems or issues that users encounter when using the software and provide insights into ways to improve the efficiency of the software (Moran, 2019).
b. Heuristic evaluation: This method involves having a small group of experts review the software and identify any issues based on established principles of usability. This can provide valuable insights into the functionality of the software but may be limited in its

ability to capture the perspectives and experiences of a representative sample of users (Ssemugabi & Villiers, 2010).

c. Expert review: This method involves having a single expert review the software and identify usability issues. This can be a useful technique for identifying specific usability issues, but may not provide a comprehensive view of the usability of the software (Harley, 2018).
d. User experience (UX) evaluation: this is a more comprehensive approach to evaluating software usability that takes into account the overall user experience of the software, including factors such as user satisfaction, functionality, and effectiveness (Kaisa and Virpi, 2008).

Studies have shown that early usability testing is a key factor in determining whether a software will be designed with users in mind or not (Lárusdóttir 2011). Users are more likely to adopt and continue using software that is easy to use and effective for their needs. User interface design, plays a crucial role in determining the efficiency of the software. A well-designed user interface can make the software easier to use and more intuitive, while a poorly designed user interface can make the software confusing and frustrating to use. All these are dependent on early usability testing.

METHODOLOGY

The research methodology adopted for this study is a combination of qualitative and quantitative methods. Integrating the two methodologies will not only give various viewpoints on the study's research aim and objectives, but it will also improve the quality and depth of the entire research process and findings (Bouma 2000).

The usability testing was carried out in the United Kingdom and Nigeria and the process included focus groups discussion, questionnaires and interviews. It has been argued that the focus group approach is a quick and inexpensive way to get information from experts and users. It can give content-rich, qualitative data and highlight findings that would be difficult or expensive to get using other approaches (Kontio, et al., 2004).

Focus group discussions: Three sets of focus group discussions (one face-to-face and two online/virtual focus group discussions) were held with a total of 33 participants to gather qualitative data about the usability of the software application. The focus group discussions were used to obtain the participants' opinions, preferences, and experiences with the software design. The focus groups aimed to understand how users interact with the software, identify areas for improvement, and gather suggestions for enhancements. By having a group of participants, the focus group discussions allowed for a more interactive and dynamic discussion, encouraging the exchange of ideas and opinions. Holding both face-to-face and online/virtual focus groups allowed the researchers to reach a wider range of participants, and gather data from both in-person and remote users.

Questionnaire survey: The questionnaire survey was used to gather data in a structured and standardized format. The questionnaire survey consisted of a set of questions aimed at gathering feedback and opinions on various aspects of the software's usability, such as ease of use, functionality, and overall satisfaction. The questionnaire survey was conducted using SurveyMonkey, a widely used online survey tool. 29 out of 33 professionals (97%) who participated in the focus group filled out the online questionnaire survey.

Interviews: The interviews were conducted to gather more in-depth and personalized feedback from the participants. Interviews were conducted with about 16 out of the 33 participants in the focus groups. The interviews were recorded with the consent of the interviewees and then transcribed for analysis.

The literature review reveals that previous research has explored various methods to conduct usability testing, including focus groups, interviews, and questionnaires. For instance, Kontio's (2001) study on software engineering risk management utilized interviews to gather information on risk management practices. Similarly, Lehtola, et al., (2004) study on requirements prioritization challenges utilized a questionnaire to collect data from software professionals. Furthermore, Sunikka's (2004) study on the usability evaluation of the Helsinki School of Economics website used a combination of usability tests, interviews, and questionnaires to gather data from users. Therefore, in line with these previous studies, the current study adopts a mixed-methods approach to conduct usability testing. The use of these methods enables a comprehensive understanding of the usability of the software, from both user and expert perspectives, and can inform possible reviews of the user interface (UI) before commencing the development of the software.

The participants in the study included industry practitioners, academics, and software/Information Technology (IT) professionals, providing a diverse range of perspectives and feedback. By combining these different methods, the researchers aim to gather a comprehensive understanding of the usability of the LeanBuild software application and to identify opportunities for improvement.

The responses obtained from the participants (both the focus group, questionnaire and interview) were analysed using descriptive analysis. Inferential statistics were not conducted because the sample size is very small and the purpose of the survey was not for generalisation, but basically to rate the respondents' opinions on the factors of the software.

RESULTS AND DISCUSSION

The section presents the analysis and discussion of the results obtained from this study.

ANALYSIS OF RESPONDENTS

The questionnaire results provide some useful information about the background and experience of the respondents, as well as their familiarity with the internet and software tools, particularly project management software.

The respondents' professional backgrounds and years of experience are presented in table 1.

Table 1: Participants' Professional backgrounds and years of experience

Professional background	% of Respondent	Years of Experience	% of Respondent
Industry Practitioners	72%	Not more than 5 years	21%
Academics	14%	5 to 10 years	17%
Software/IT Professional	14%	10 to 15 years	38%
		More than 15 years	24%

The respondents include industry practitioners, academics and software/IT professionals. In terms of experience, the results indicate that the respondents are fairly evenly distributed across different levels of experience. This suggests that the views and insights of the respondents may be representative of a diverse range of career stages and backgrounds.

The results also indicate that all the respondents have an appreciable knowledge of the internet and the use of software, which is an important factor in conducting online surveys and using software tools for project management. However, it's notable that only 41% of the respondents have used project management software before, which suggests that some respondents may be less familiar with this type of tool and may need additional guidance or training in its use.

COMMON USABILITY PROBLEMS EXPERIENCED BY USERS OF PROJECT MANAGEMENT SOFTWARE

Based on the survey and interview results, it is clear that data privacy and security are major concerns for end users. Approximately 83% of the participants recommended that data must be controlled by subscribing organizations to ensure data privacy and security. This indicates that data privacy and security should be a top priority when developing software. To address this concern, the development team would focus on incorporating top-notch security features into the software to ensure the end-users data is secure and protected.

According to the feedback received from the questionnaire, participants suggested that the software should include a budget approval process and a disbursement process. This would enable project managers to track and manage project costs more effectively. This will ensure that budget limits are not exceeded. Another issue raised was that the software should be more colourful and visually appealing. Some respondent noted that the software's current interface is more academic than practical, which could lead to less user engagement. This concern highlights the need for the software to be designed with the end-users in mind, making the interface more visually appealing, and enhancing user experience (Lárusdóttir, 2011).

Additionally, the survey and interview results indicated that there is a need for the software to offer more features and functionalities. Participants noted that the current design of the software has a limited scope and function, which can limit its usability. To address this concern, the development team would consider adding more features and functionalities to the software to provide more value to the end users.

THE COMPREHENSIVENESS OF THE LEANBUILD SOFTWARE DESIGN FLOW

The questionnaire results suggest that a large majority of the respondents (86%) agree that the documents listed on the project initiation homepage are comprehensive enough to initiate a project, while 14% neither agree nor disagree. This indicates that most of the respondents perceive the listed documents as sufficient for initiating a project. To ensure the comprehensiveness of the documents listed, the researchers compared the listed documents against established best practices and standards for project initiation to determine their adequacy and completeness.

The questionnaire results show that a significant majority of the respondents (83%) agree that the documents listed on the project planning page are all the documents needed for the scope management planning of a project. However, 17% of the respondents neither agree nor disagree, which suggests that they may have some uncertainty or lack of clarity about the completeness of the listed documents. One possible explanation for the disagreement or uncertainty among the respondents could be that they have different levels of experience or expertise in project management or scope management, which may influence their perception of what documents are needed for effective planning. A respondent suggested the addition of an accounting interface and project responsibility flow to the software.

In the case of the cost planning sheet, the majority of the respondents (79%) agree that it represents the standard bill of quantities for a typical construction project. However, a notable percentage (14%) disagreed with this statement, while a smaller percentage (7%) were undecided. Respondents suggested providing a feature for budget approvals, cash flow, and disbursement to manage and control costs. Regarding the TVD user interface, the results indicate that a significant majority of the respondents (86%) agreed that it captures the detailed working principles of TVD. However, a smaller percentage (14%) were undecided. The majority of the respondents (69%) agreed that the TVD "set targets" interface covers all the typical project constraints, while a significant percentage (28%) were undecided. This suggests that some respondents may not have a clear understanding of TVD principles and its associated constraints, or may need more information to fully evaluate the "set targets" interface. Further clarification and explanation may be needed to ensure that all respondents have a common understanding of TVD and its associated constraints.

In regards to the execution page user interface, a large majority of the respondents (89%) agreed that it captures all the necessary activities for the execution stage of a typical project, while a smaller percentage (11%) were undecided. This suggests that the majority of respondents perceive the interface as comprehensive enough for the execution stage of a typical project. The respondents suggested the addition of task flow and project report interface.

Similarly, for the control schedule page user interface, a significant majority of the respondents (86%) agreed that it captures all the necessary elements for controlling the schedule of a typical project, while a smaller percentage (11%) were undecided, and a very small percentage (3%) disagreed. This indicates that the majority of respondents perceive the interface as sufficient for controlling the schedule of a typical project, but some may have reservations or uncertainty about the completeness of the interface.

Results also show that all respondents agreed that the construction project data model is well represented in the user interface (UI). This is a positive finding that indicates that the UI is effective in presenting the data model to the users (Hornbæk, et al., 2007).

The Ease of Use and Effectiveness of the Leanbuild Software

The questionnaire results indicate that the majority of respondents find the user interface of various project management software clear, easy to understand and implement. Specifically, 93% agreed that the layout of the project initiation homepage and the project planning user interface is clear and easy to understand. Furthermore, 96% agreed that the labels and instructions for using these pages are clear and concise. Regarding the appropriateness of the visual elements used in the user interface, most respondents agreed with the project initiation homepage (75%) and the project planning user interface (81%). However, some respondents (17%) were undecided about the appropriateness of the visual elements used in the initiation homepage UI. This means there is still room for improvement (Dillon, 2014).

Similarly, the cost planning sheet user interface, Set Target user interface, and the execution stage user interface are also clear and easy to understand, with over 90% agreement. Some respondents were undecided about some aspects of the UI, such as the visual elements used in the project planning UI (15%) and the labels and instructions for using the software (15%).

However, when it comes to the design of the UI, the results were somewhat mixed (Bruun, and Stage, 2015). While most respondents found the colours, fonts, and other visual elements used in the project initiation homepage UI to be appropriate, only 75% agreed that they were appropriate for the project planning UI.

This survey result shows that the majority of participants (77%) gave a score of 8 or higher on the recommendation scale, indicating that they are likely to recommend the software to a friend or colleague. 42% of participants gave the highest score of 10, indicating that they are extremely likely to recommend the software. 8% gave a score of 9, which is still a high score. 35% of participants gave a score of 8, which is a somewhat likely score. Finally, 15% of participants gave a score of 7, which is a neutral score indicating that they might recommend the software but with some hesitation.

Overall, the results suggest that the UI is effective in presenting the construction project data model, and the labels and instructions are clear and concise (Bruun, and Stage, 2015). However, some improvements may be necessary for the design of the UI to ensure that it is visually appealing and appropriate for all users.

FINDINGS AND RECOMMENDATIONS FROM INTERVIEWS

The interview results provide valuable feedback and suggestions for improving the LeanBuild software. The figure 1 shows the various suggestions and number of interviewee that made the recommendation.

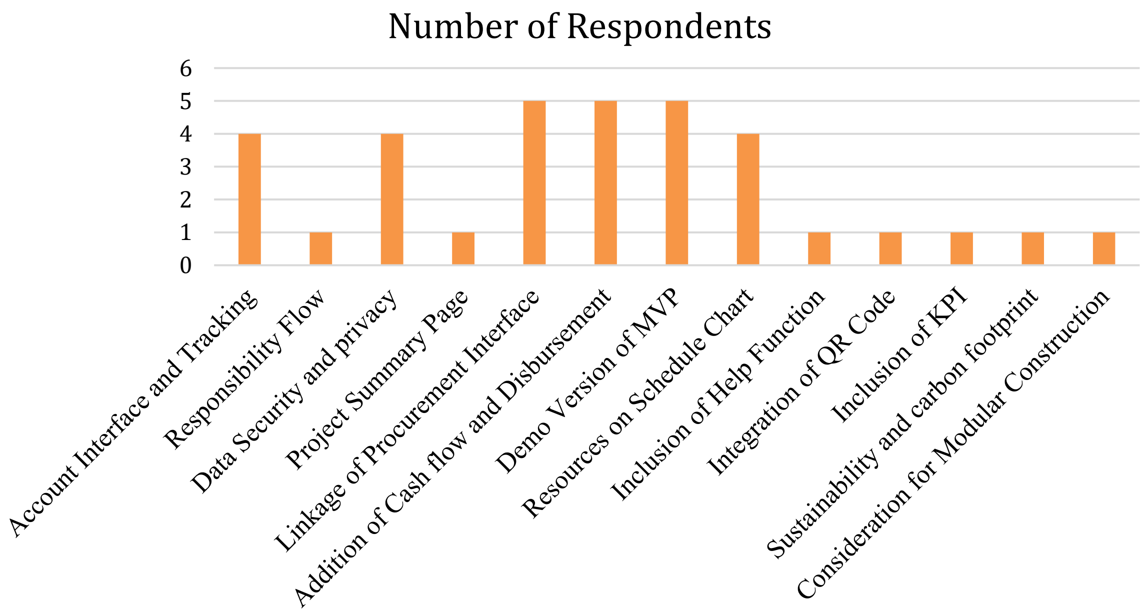

Figure 1: Suggestions and Number of Respondents that Made the Recommendation

Figure 1 shows the recommendations for improving the LeanBuild software. Some of the key suggestions include adding an account interface and tracking feature, defining responsibility flow and linking line management to activities, capturing variation of material and material diversion, providing budget approvals, cash flow, and disbursement, and offering a demonstration version of the software. The respondents also suggested the addition of resources to the schedule tracking chart to show the volume of resources required, and making the Gantt chart flexible enough to accommodate changes. Also the software should include a help function and screen guide; and integrate Building Information Modeling (BIM), Microsoft Project files, QR Codes for inventory management, Key Performance Indicators (KPIs), Artificial Intelligence (AI), sustainability and carbon footprints measurement (Sawhney and Odeh, 2020). The respondents also recommended that a provision should be made to capture the variation of material, and linkage of activities on the procurement interface. Finally, they suggested incorporating the features that support emerging trends in off-site and modular construction. The interview feedback has helped to validate the findings of the focus group and questionnaire survey. It also provides valuable insights into improving the LeanBuild software, and incorporating the suggestions provided would enhance the software's overall effectiveness and user experience.

CONCLUSIONS

The study evaluated the usability of the LeanBuild software application after the design stage of software development. Literature on current project management software was reviewed and the most common usability problems were identified. Attempt was made to determine the comprehensiveness of the design flow, the ease of use and effectiveness of the LeanBuild software application.

The research adopted a hybrid of qualitative and quantitative methodologies which include focus groups, questionnaires, and interviews. Integrating the two techniques not only provided different perspectives on the study's research aim and objectives, it also increased the overall quality and depth of the research process and findings. The study participants/respondents include industry practitioners, academics and software/IT professionals – as such views and insights of the respondents represents diverse range of career stages and backgrounds.

The results show that data privacy and security are important to end-users, and that the software should include a budget approval and a disbursement process. There were also suggestions for additional features, such as an accounting interface and project responsibility flow. The majority of respondents perceive the designed user interface to be sufficient and comprehensive for initiating, planning, executing, monitoring & controlling, and closing a typical project. Overall, respondents find the user interface of the project management software clear, easy to understand, and implement. The majority of participants have a positive view of the LeanBuild software and are likely to recommend it to others, which is a good sign for the software's success.

The implication of this research for researchers and software developers is that the paper has established that it is possible and better to identify usability issues early by conducting early usability test after the design stage. The limitation of the study includes small sample size and limited generalizability. Finally, the paper presented a digital technology that construction experts have been advocating for. This digital technology is a project management software that covers the complete lifecycle of a typical construction project. And also incorporated TVD and traditional construction methodology. The paper has also demonstrated that it is advantageous to conduct early usability test after the design stage of the software development cycle.

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ENVIRONMENTAL IMPROVEMENTS FOR RENOVATION WORK USING LASER SCRAPING

Kaori Nagai[1], Motoki Imazeki[2], Yasuaki Kaneko[3], and Yuuki Kawai[4]

ABSTRACT

Construction sites in general are in environments where noise, vibration, and dust including. Especially in renovation and demolition works, concrete cutting, drilling, and scraping require not only loud noise, vibration, and dust, but also long hours of reaction force from the workers to use the machinery. Robotization has progressed in recent years and the environment for workers is improving, but the working environment in general sites where robots are difficult to install remains a challenge.

This study aims to develop a method to improve the noise and other working environments of refurbishment works. This paper describes the results of a feasibility study on a laser scraping method to reduce noise in the renovation of infrastructure facilities around residential suburban areas.

The results show that thin cement adhering to the rebar can be removed by the low power laser. Furthermore, a comparison of the noise level with conventional methods on site confirmed the superiority of laser scraping. This result indicates, in terms of lean construction, will reduce waste and improve the quality of the site.

KEYWORDS

Renovation, Environment, Sustainability, Concrete, Laser.

INTRODUCTION

Concrete structures built during the period of high economic growth are aging, and deterioration phenomena such as cracking, floating, and peeling are becoming apparent. There are various methods for repairing and renovating deteriorated concrete structures, and appropriate methods are selected according to the deterioration phenomena and surrounding environment. In the sectional repair method, one of the repair methods for concrete structures, the process starts with concrete removal, followed by reinforcement cleaning, corrosion protection, and sectional repair. It has been reported that the quality of the surface of the reinforcement after reinforcement cleaning affects the performance after repair (Kunieda 2010).

For example, in sectional repair work of concrete structures, concrete removal is performed using water jets or similar tools, and it is necessary to completely remove the mortar adhering to the reinforcement using tools such as jet chisels. At that time, it has been reported that incomplete removal can cause re-corrosion of the reinforcement (Watanabe et al. 2013).

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In conventional reinforcement scraping, jet chisels and cup brushes are used to remove cement paste adhering to the reinforcement. Miyamoto (1973) reported that there is noise and vibration of 80 dB or more at 30 m from the work point in on-site concrete demolition work. In particular, sufficient consideration is required for elevated roads passing through residential areas in urban areas. Jet chisel work is essential due to the increasing number of infrastructure rehabilitation projects. This operation is one of the most difficult tasks to manage the process because of the limited working hours due to the loud noise. However, although some tools have been developed for scraping or chipping concrete, they have little effect on noise reduction. Therefore, we focused on laser technology as a new means of rebar cleaning that can reduce the burden on the work environment.

In recent years, laser technology has been considered for its applicability as a new surface treatment method for removing rust from metal material surfaces and has been implemented as laser cleaning work. Shirakawa et al. (2005) conducted an experiment to remove rust from iron towers using a 280W YAG laser. As a result, it was reported that laser cleaning improved adhesion of paint compared to cleaning with a metal brush. Hino et al (2018) reported that cleaning of metal materials is possible for various types of dirt by using a 3 kW YAG laser. In addition, Nishihara et al (2019) cleaning of molds is performed using a 70W fiber laser to remove dirt and oil from metal surfaces. Zhihu Zhou et al. (2023) have also explained the mechanism of laser cleaning and confirmed its effectiveness for cleaning metal and non-metal materials. Matsui (2003) reported the superiority of using lasers for graffiti removal on concrete. Although research on rust and paint film removal from metal substrates has been conducted in this way, no research has been conducted on the removal of cement materials adhering to steels.

In the philosophy of lean construction (Koskela 1997), this research is a development that will improve the quality of construction and the environment of on-site cleaning work. In this study, the research is aimed to develop a low-vibration, low-noise, low-dust, and reactionless method that can remove 1mm thick concrete scraping to reinforcing bars after the concrete is removing and red rust remaining after removal. The experiment is to use a portable laser of 200W and less for use at construction sites. This report describes the results of basic and applied experiments on the laser cleaning method using an understanding of the thermal effects of mortar, laboratory tests, and trial construction at actual sites.

MECHANISM OF LASER SCRAPING

The principle of laser scraping is shown in Figure 1. Laser scraping works by utilizing the ablation that occurs during laser irradiation. This involves instantaneously decomposing substances adhering to the surface layer of the irradiated area with laser light, and evaporating and sublimating them in the process while removing the target substance as long as it continues to absorb the energy of the laser in combination with the micro shock waves generated.

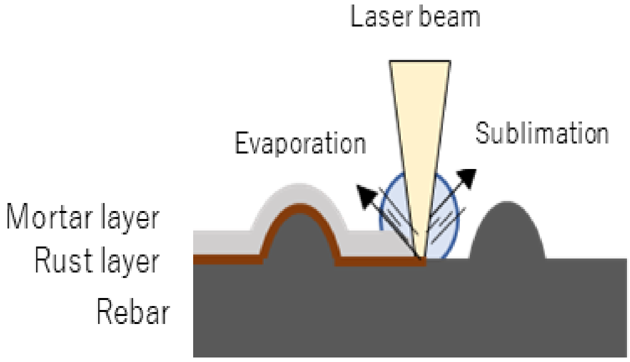


Figure 1: Laser scraping diagram

In this study, the test is tried with a low-power laser to remove 1 mm of cement without affecting the rebar. As shown in Figure 1, efficient irradiation can be achieved by using a galvanometer mirror to scan the laser light at high speed on substances adhering to the surface layer. At this time, the laser energy density that causes ablation of the target material must always be higher than the energy density that causes ablation of the base material. This allows only the target material to undergo ablation without affecting the base material, making it possible to remove only the target substance.

LASER IRRADIATION EXPERIMENT

PURPOSE OF EXPERIMENT

This experiment verifies the removal performance using 100W lasers, based on the results of an experiment using mortar plates, to select laser irradiation conditions assuming a construction site.

CONDITION OF EXPERIMENT

The specimen is shown in Figure 2 and the irradiation range is shown in Figure 3. Assuming a structure such as a bridge, the specimen consisted of five D16 rebar's crossed at intervals of 130 mm and covered with 1 to 2.5 mm of mortar. The mortar adhered to the specimen was a premix TDR mortar (Hirama 2006) except for the vinylon fibers, and the external dimensions of the specimen were 950 x 950 mm. This mortar is repair materials for concrete structures.

Figure 2: The specimen

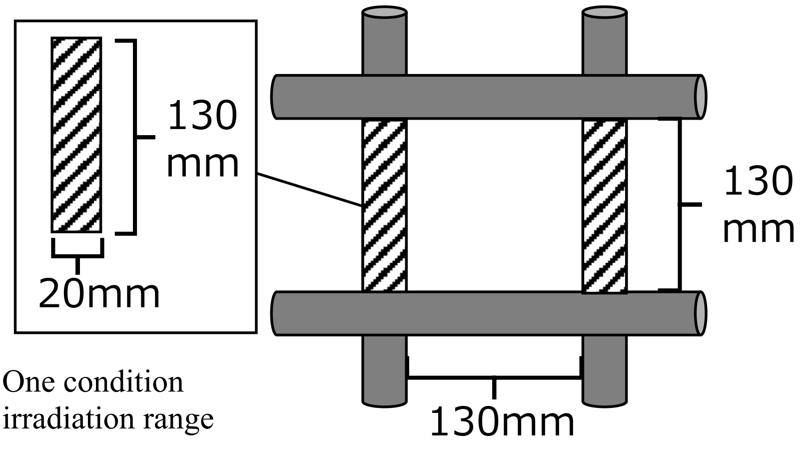


Figure 3: Laser Irradiation area

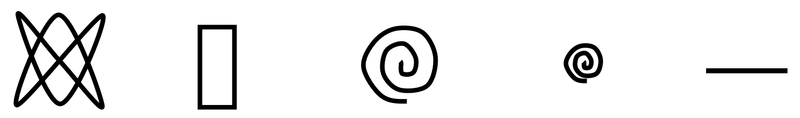
EXPERIMENTAL METHODS

Irradiation conditions are shown in Table 1 and scanning geometry in Table 2. Among the irradiation conditions, the frequency was selected from the preliminary experiments to have high removal performance. In addition, the laser beam was scanned and irradiated to each shape to improve the removal efficiency. An irradiation schematic is shown in Figure 4.

Table 1: Laser Irradiation Condition

Power (W)	Mode	Frequency (kHz)	Irradiation Speed (mm/s)	Irradiation time (s)	Focus distance (mm)
100	パルス	70	0.3 0.6 0.9 1.2 1.5	180	163

Table 2: Scanning Geometry



Lissajous	Rectangle	Spiral-L	Spiral-S	Beeline

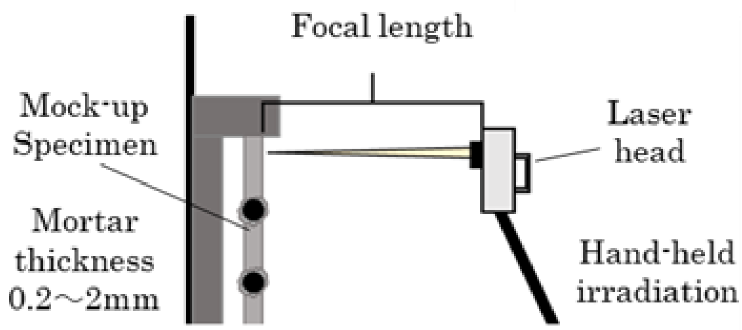


Figure 4: Laser irradiation schematic diagram

EVALUATION METHODS

Surface observation: Mortar and rust residues were visually checked after laser irradiation.

Removal rate: The removal rate was calculated from the images of the specimen after irradiation and after the use of a cup brush, using processing software to determine the evaluation area and the area of mortar removed.

Working time: The time required for the work was measured at two levels: the time required for laser irradiation alone, and the total time required for cup brush removal as a secondary process for the remaining areas. In the cup brush removal process, the completion of mortar and rust removal was visually determined.

RESULTS OF EXPERIMENT

The results of the removal performance under different laser irradiation conditions are shown in Figure 5. The graphs compare the results of the 100 W results of this experiment with data from the author's previous studies conducted using a 200 W fiber laser (Imazeki 2022). It was found that the removal rate of the 100W laser was lower than that of the 200W laser under all conditions when using the laser alone. However, when a cup brush was used after irradiation with both the 100W and 200W lasers, almost the same level of removal rate was achieved. Considering that the mortar thickness of the mock-up created in this study ranged from 1mm to 2.5mm, it can be inferred that even 1mm thick mortar, which was the original target, could be removed using the laser alone, and thicker mortars could also be weakened by the heat generated by the laser. Furthermore, each laser machine used in this study had a different spot diameter, with the spot of the 100W laser being smaller. This factor may have contributed to the ability to weaken the mortar by achieving a similar power density as the 200W laser.

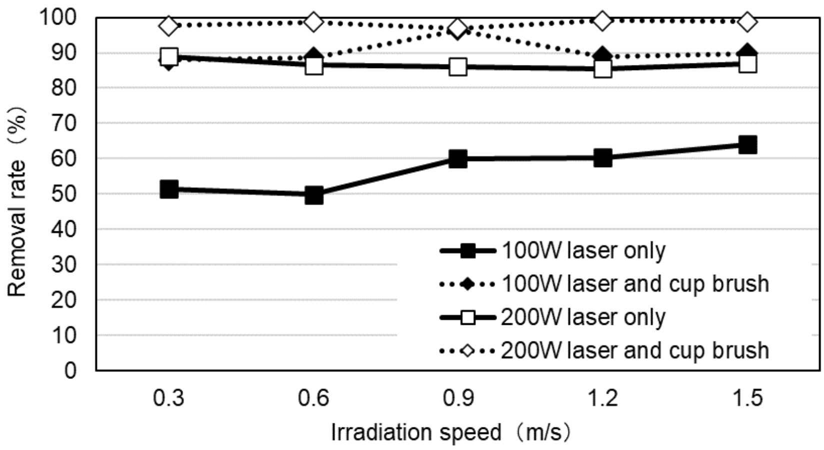


Figure 5: Comparison of removal performance

A comparison of scanning geometries is shown in Figure 6. In this experiment, a change in the removal rate after each operation was observed depending on the scanning geometry. The two types of spiral shapes tended to have higher removal rates, with the Spiral-S with a smaller diameter showing higher removal rates. The high removal rate of the spiral shape was also observed even when a cup brush was used, indicating that, among the scanning shapes, the spiral shape was more prone to heat accumulation in the center of the mortar because the laser beam was irradiated from the center towards the outside.

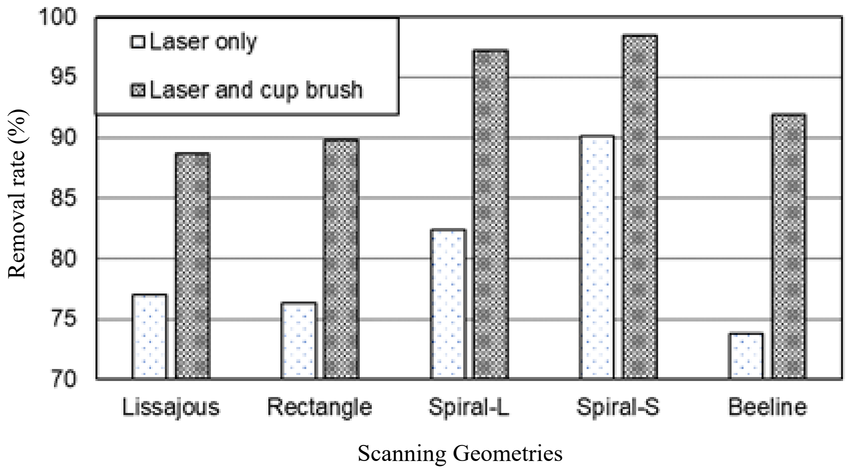


Figure 6: Comparison of scanning shapes

According to brittleness of the mortar. Furthermore, the maximum removal rate was 98.5% when the cup brush was used in combination with the laser beam, indicating the potential of laser scraping even with the 100 W laser, which is low power.

ON-SITE TESTS

TEST OVERVIEW

The field test construction location is shown in Figure 7. The construction site was the overhang of the slab on which the sectional repair was being constructed, in a space surrounded by a light-emitting soundproofing sheet. The concrete removal was completed and the rebar was exposed before the cleaning work was carried out. The rebar in question was φ13 round steel. For the test construction, one condition of laser irradiation was applied to one span (150 mm) of the assembled rebar.

The laser irradiation conditions were as follows: frequency 70 kHz, focal length 163 mm, irradiation speed 10 m/s, and two types of spirals with different irradiation diameters as the scanning shape. The irradiation time was not decided beforehand and was carried out at the discretion of the laser irradiation operator. As a comparison, a conventional cleaning method using a jet tool and a cup brush was also carried out. The end point of the cleaning work using the tools was determined at the operator's discretion.

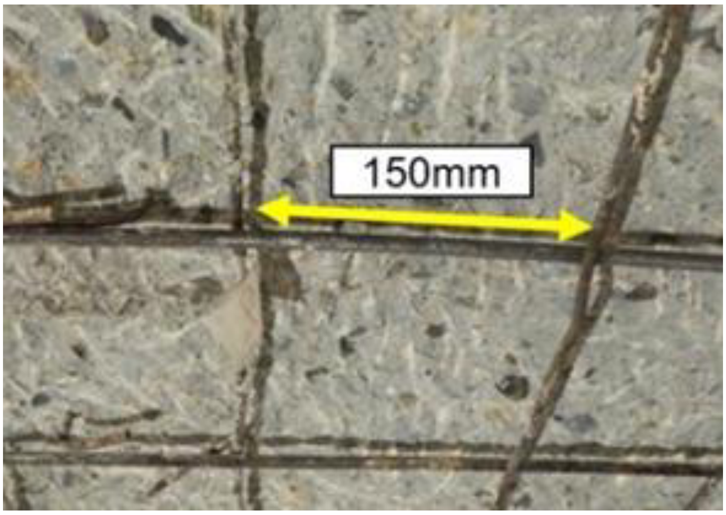


Figure 7: Irradiation area of on-site demonstration test

EVALUATION METHODS

The surface condition was checked when laser irradiation and cup brushes were used. The evaluation was based on the surface finish and compared with the conventional method.

The time required for laser irradiation and the time required to clean the surface using tools were measured using a stopwatch. Only the working time was measured and the comparison was made without including the time required for changing tools.

Measurements were taken using a digital dust meter (S) to measure the amount of dust prior to the cleaning work, during laser irradiation, jet chisels and cup brush application for 2 minutes. The average value of the measured dust amount was organized as a relative index with the dust amount before the installation set as 1.

Measurements were taken during each operation using an ordinary sound level meter (manufactured by Company R), and the measured values were expressed as equivalent noise level Leq (dB). Dust and noise were measured at a distance of 2 m from the workers.

RESULTS OF ON-SITE TESTS

Figure 8 shows the condition of the surface during the field test installation and Figure 9 shows the condition before and after scraping. As in the verification of the mock-up specimen, the laser irradiation was able to remove rust and thin mortar, but not all mortar could be removed by laser irradiation alone. However, by using a cup brush to clean the surface after laser irradiation, it was possible to achieve a finish comparable to that of the conventional method (combination of jet chisels and cup brush).

Figure 8: On-site demonstration test situation

Before scraping.	
After laser irradiation	
After laser irradiation and cup brush work	

Figure 9: On-site rebar before and after scraping work

The working time per unit length is shown in Figure 10. The conditions in which laser irradiation was carried out increased the time required to clean the rebar compared to the conventional method. However, the time required for cup-brushing work was similar for all conditions.

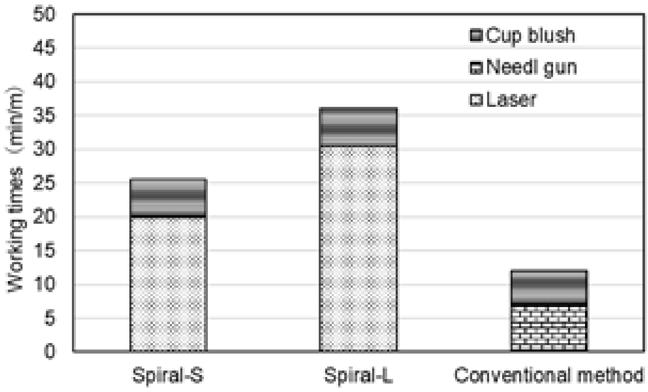


Figure 10: The results of Working times

The results of the dust measurements are shown in Figure 11. The objective of this experiment was to confirm the relative dust reduction effect. For this reason, the relative dust amount was organized as the dust amount before the construction (initial value) was set to 1.

It was confirmed that the amount of dust during laser irradiation was approximately 1/4 of that of a cup brush and 1/10 of that of a jet chisels, and that dust could be reduced significantly compared to the conventional method.

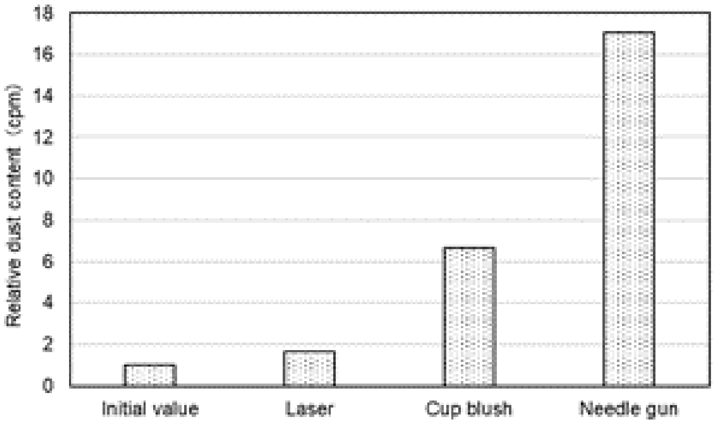


Figure 11: The results of dust measurement

The results of noise measurements are shown in Figure 12. The initial equivalent noise level during on-site work was 64.1 dB. The noise levels during each operation were 66.6 dB for laser irradiation, 92.6 dB for cup brush operation and 96.3 dB for jet tagger operation, and the equivalent noise levels for laser irradiation only were approximately 3/4 and 2/3 of those for cup brush and jet tagger respectively. The equivalent noise level during laser irradiation was similar to the initial value, confirming that laser scraping is less noisy than the conventional method.

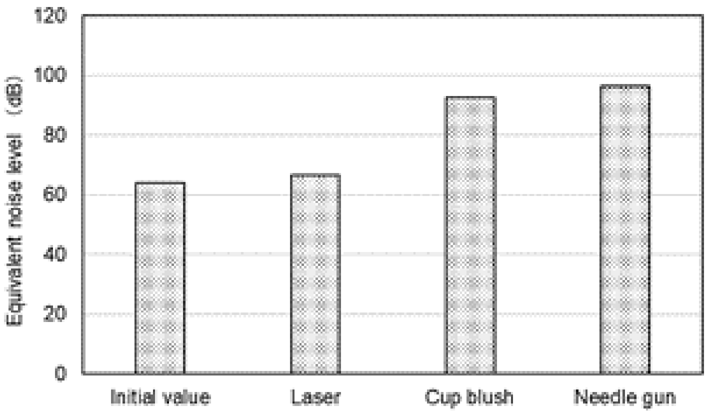


Figure 12: The results of noise measurement

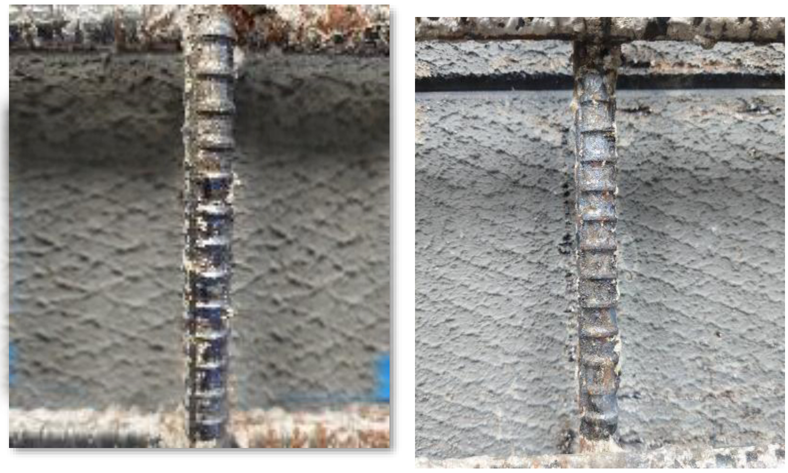
DISCUSSION AND FUTURE ISSUES

KAIZEN OF SCRAPING WORK BY LASER

In this study, we confirmed that it was possible to use a 100W low-power laser on two types of materials: thin cement layers and rust (Figure 13). Previous studies have mostly focused on the removal of paint or rust from iron plates, where the materials were single and several hundred micrometers thick.

In laser processing of concrete, it has been reported that it vitrifies due to high temperature at 3kW or more (B. Tirumala Rao et all 2005). On the other hand, if the exposure time is short even at high power, the thermal influence on the material is small, and it has been reported that holes can be made in concrete (Nagai et al, 2018). In addition, the possibility of chipping the surface of concrete with about 500W has been reported (Kamata et al, 1996). From these results, since the target of this study is a thin cement layer, it was thought that cement could be made brittle with low power and it was possible to demonstrate it.

This development can contribute to the improvement and quality enhancement of lean construction sites. The work time for digging in renovation projects can be long depending on the site conditions, or limited by noise problems. However, this development makes it possible to plan work hours. Furthermore, it is effective in reducing power consumption on site by making it smaller and simplifying its handling. Future research should be conducted to further reduce working hours.



200W Laser 100W Laser

Figure 13: Compare of 200W Laser and 100W Laser

IMPROVEMENT OF WORK ENVIRONMENT

As a result of our examination of noise, vibration, and reaction force issues at construction sites, we have found that laser construction reduces noise problems and allows for renovation work to proceed in environments such as urban areas and near hospitals. Furthermore, the work environment for workers is clearly improved, and the use of non-reactive non-vibration scraping construction can contribute to reducing the burden on workers.

In the future, we believe that incorporating robots will lead to further improvements in the work situation.

REDUCTION OF GLOBAL ENVIRONMENTAL IMPACT

As a result of field tests, it was confirmed that the amount of dust generated is almost negligible. This is due to sublimation by laser. In mechanical processing such as water jetting and sandblasting, a large amount of water and sand is used, resulting in a large amount of dust and an increase in waste materials. These problems can be improved by using lasers.

In the future, further environmental improvements can be expected by suctioning the small amount of dust generated.

CONCLUSION

It was confirmed that mortar and red rust as thick as 1 mm could be removed even with a low level of laser irradiation of 100 W. Furthermore, for mortar thicker than 1 mm, the heat from the laser irradiation tended to weaken the mortar in a short time, reducing the cup brushing time. In the field, the combination of laser cleaning and cup brushing was found to provide removal performance comparable to conventional methods without the noise and vibration. This method was found to be effective in improving the environment for workers and excellent in areas where noise and dust control measures are difficult to implement.

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A FUZZY FRAMEWORK FOR CONTRACTOR SELECTION ON IPD PROJECTS

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ABSTRACT

The construction industry is characterized by complexity, budget and schedule overruns, quality and safety problems, and increased claims and disputes. To successfully manage the inherent complexity of construction projects, optimal contractor selection is integral for project success. Choosing the best-fit contractor is especially important in Integrated Project Delivery (IPD), since this procurement route relies heavily on the efficient collaboration of project stakeholders and necessitates trust to guarantee successful outcomes. However, the numerous methods and tools for contractor selection in the literature target traditional delivery routes and are unsuitable for IPD, considering the latter's distinct features and stakeholder roles. As such, owners transitioning to IPD do not fully understand the requirements for optimal contractor selection, which jeopardizes the success of IPD projects. To address this need, this paper conducts a comprehensive literature review and investigates twelve unique IPD case studies to identify contractor selection criteria important to IPD. The paper presents a decision-making framework for contractor selection in IPD projects, using the Fuzzy Inference System (FIS), that provides an indication of the best-fit contractor for the IPD project. This research fills a significant gap in the literature by providing a tool to assist IPD practitioners to select the right contractor.

KEYWORDS

Contractor selection, fuzzy inference system (FIS), integrated project delivery (IPD), qualification-based selection, multi-criteria decision-making (MCDM) tool

INTRODUCTION

The construction industry is characterized by complexity, budget and schedule overruns, quality and safety problems, and increased claims and disputes (Singh and Tiong, 2005). Since construction projects heavily rely on the interaction and collaboration of different parties (El-Sayegh et al., 2021), and since contractors play a major role on such projects, it is widely agreed that optimal contractor selection is integral to manage the inherent complexity of these projects (Mousakhani et al., 2018). Accordingly, having the right contractor on board is critical to determining project success or failure (Vardin et al., 2021) as appointing the most suitable

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contractor is a prerequisite for successful project outcomes (Fong and Choi, 2000; Jafari, 2013; Zhang et al., 2016). Furthermore, Kog and Yaman (2014) underline the importance of having a strong and steady relationship between the client and the contractor to achieve project goals. On the other hand, inappropriate contractor selection leads to bad quality works (Alptekin and Alptekin, 2017), delays, cost overruns, poor performance, accidents, bankruptcy, disputes (Abdul Razak et al., 2021), and project failure in terms of quality, cost, and time (Mousakhani et al., 2018).

"Integrated Project Delivery (IPD) is a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction" (AIA, 2007). Considering the unique characteristics of IPD and its reliance on the efficient integration and collaboration of project stakeholders, it is crucial to select suitable project participants with shared goals and established trust and cooperation to guarantee the successful implementation of integrated projects (Zhang et al., 2016). In this regard, selecting a project team that collaborates efficiently has been identified as a prerequisite to effective IPD implementation (Townes et al., 2015). Therefore, it can be argued that appropriate contractor selection for IPD projects is of even greater importance than for other traditional project delivery routes.

While numerous studies in the literature attempt to propose methods for contractor selection for traditional delivery routes, these traditional practices and selection methods are not suitable for IPD projects (Zhang et al., 2016; Townes et al., 2015). Zhang et al. (2016) emphasize that different criteria and techniques must be considered when selecting contractors for IPD projects, since this delivery route has distinct features and imposes different roles and obligations on the participants. Nevertheless, there is a lack of studies on IPD party selection, and the existing literature fails to sufficiently investigate how IPD contractors should be assessed and compared (Townes et al., 2015). Furthermore, an investigation of the contractor selection process in twelve IPD projects published by the AIA "IPD Case Study Matrix" in 2012 reveals that, while certain IPD-related criteria are considered, there is no standardized or published decision-making framework utilized for this process. Due to the present state of knowledge, project owners transitioning to IPD do not fully understand the requirements for selecting an optimal contractor for this delivery route, which jeopardizes project success (Townes et al., 2015). Therefore, considering the established importance of appropriate contractor selection for construction projects in general, and IPD in specific, and considering that the traditional selection methods and criteria are not suitable for IPD, there is a clear need to establish a framework for contractor selection on IPD projects.

This paper conducts a comprehensive literature review to identify the criteria used for the assessment and selection of contractors for construction projects. In addition, the paper further investigates twelve unique cases of IPD projects, published by the AIA, to identify IPD-specific criteria utilized in this process. Ultimately, the objective of the paper is to develop a decision-making framework for contractor selection in IPD projects that utilizes the user's rating of the identified criteria as inputs and provides, as an output, an indication of the best-fit contractor for the IPD project at hand. This research fills a significant gap in the literature by providing criteria and a framework for evaluating and selecting contractors on IPD projects. The proposed framework can be customized according to the stakeholders' needs and preferences on the specific project it is applied to. This decision-making tool will assist practitioners entering IPD projects in selecting the right contractor to optimize the chances of project success.

METHODOLOGY

The methodology of the paper followed the below 5 steps.

1. Identification of Contractor Selection Criteria for Construction Projects: A systematic literature review was conducted, based on the guidelines by Hong et al. (2012), to identify the criteria for contractor selection on construction projects, with a specific focus on IPD projects. Accordingly, the authors performed a selective search to find articles with the following phrases in subjects, titles, keywords or abstracts: contractor selection “and/or” criteria, factors, frameworks, IPD, and methods. The abstracts of the articles were then reviewed in detail to assess their relevance and criteria were identified from the research.
2. Identification of Contractor Selection Criteria for IPD Projects: Subsequently, the authors studied and analyzed twelve cases of IPD projects published by AIA IPD Case Study Matrix (2012) to establish a stronger understanding of the process of contractor selection in real IPD projects. From these cases, further criteria relevant to contractor selection were identified.
3. Filtering, Sorting, and Grouping the Established Criteria: Next, the factors identified from the first two steps were analyzed, filtered by removing redundancies, grouped into sub-factors, and organized under a hierarchy to prepare for the execution of the FIS modeling.
4. Constructing the Rubric for Measuring the Factor Input: A rubric was developed to maintain consistency in rating the metrics. The rubric describes the input degrees of each factor in practical terms.
5. Modeling Using Fuzzy Inference Systems (FIS): The framework is constructed using FIS, which was chosen due to (1) its ability to manage and represent qualitative factors, considering that certain factors identified for IPD contractor selection are qualitative in nature, and (2) its capacity to account for the vagueness and uncertainty of decision-makers (Hellmann 2001). The MATLAB Fuzzy Logic Designer Toolbox is used to construct the model and the Mamdani style is adopted for “being intuitive, having widespread acceptance, and well-suited to human input” (Gunduz et al. 2015). Using the Mamdani style, membership functions are assigned trapezoidal and triangular shapes, ‘if … then’ rules are applied, and the output is evaluated by calculating the centroid of the aggregated shape. For simplicity, the authors assumed a set of base rules and a standard template for the membership function applied to all factors, based on the model proposed by ElBeltagi et al. (2011). Nevertheless, when applying the tool to a specific case study, the rules and functions can be easily calibrated based on the expert opinions of the project stakeholders, which can be obtained through surveys or interviews. The FIS involves 3 stages, Fuzzification, Fuzzy Inference, and Defuzzification and follows the below steps:
    1. The user provides a crisp input by choosing a rating between 0 and 10 as per the rubric developed in Step 4.
    2. Fuzzification: Using membership functions, the input is converted to fuzzy sets.
    3. Fuzzy Inference: The fuzzy inference or the rules that determine the outcome of the outputs are applied. Each rule generates a fuzzy set which is then aggregated for the next step.
    4. Defuzzification: Using output membership functions, the sets are defuzzified after aggregating the fuzzy sets.
    5. The user then receives the final output which is a crisp result. This is an indicator of the “contractor score” on the IPD project.

LITERATURE REVIEW

The selection of the optimal construction contractor is considered the most important responsibility of the owner as this decision directly impacts project performance and outcomes (Mousakhani et al., 2018). While, traditionally, contractors were selected on a lowest-bid basis, studies have found this method to detrimentally affect project outcomes in terms of time, cost, quality, and disputes (Cheaitou et al., 2019). Therefore, contractor selection methods were developed to include multiple criteria additional to cost and utilized various multi-criteria decision-making (MCDM) techniques (Cheng et al., 2020). To this end, Sigh and Tiong (2005) presented a fuzzy model to assess the contractor's capacity to deliver a project meeting the owner's requirements and applied the tool to choose between 4 contractors. Doloi (2009) analyzed contractor prequalification criteria to determine their influence on project success. The author performed a factor analysis on 43 influencing technical attributes and extracted 7 factors that impact performance. The results show that project success in terms of cost, quality, and time is significantly influenced by a number of factors, including time in business, technical proficiency, history of success, working capital, and work methods. Jafari (2013) used the quality function deployment (QFD) method for contractor prequalification, considering both the owner's requirements and the contractor's qualifications. Marzouk et al. (2013) categorized factors influencing contractor selection into 10 main criteria and 46 sub-criteria, including cost, experience, time, safety, insurance, disputes, and risk avoidance, among others, and isolated the most important ones based on statistical analysis using surveys. Moreover, Kog and Yaman (2014) developed a multiagent system-based model to prequalify contractors. However, this was only suitable for traditional design-bid-build projects and excluded other delivery routes. Liu et al. (2015) identified several essential criteria to consider in assessing contractors, based on two-stage partial least squares path modeling. In their contractor selection method research, Mousakhani et al. (2018) used a risk-oriented approach to identify contractor selection factors and evaluated them using AHP. To select the best contractor for public construction projects, Cheng et al. (2020) proposed a Bayesian fuzzy prospect model, based on probability and utility multiplied relation. Further, to overcome the deficits of lowest bid selection, Vardin et al. (2021) used Fuzzy-VIKOR and the best-worst method to develop a contractor selection framework.

While these studies, in their selection of criteria and development of decision-making models, appear to be comprehensive, they are all related to traditional procurement routes and are not sufficient for IPD. In fact, existing studies do not adequately investigate how IPD contractors should be compared and selected (Townes et al., 2015). Nevertheless, certain researchers attempted to reduce this gap by providing insight and recommendations on the matter. As such, Rahman and Kumaraswamy's (2005) recommended pre-selection workshops for short-listed teams to select relationally integrated teams. Similarly, Dossick et al. (2013) described the adoption of 2-hour workshops in an IPD case study that involved 4 shortlisted teams who engaged in a unique proposal process. Townes et al. (2015) investigated a case study to comprehend the means and process of contractor selection on IPD projects, and detailed the different stages that took place, including the submission of proposals prepared by self-selected multidisciplinary teams and the use of pre-selection workshops for team evaluation. They described that the owner's assessment of the shortlisted teams relied on the IPD workshops and interviews conducted, which were useful for the observance and evaluation of IPD team selection criteria, including intangibles qualifications, such as collaborative performance. However, they did not provide the method for rating the criteria nor the decision-making tool used to this end. On the other hand, based on the inter-organizational transactive memory system (I-TMS), which is "a collaborative cognition division system that forms when multiple organizations cooperate with each other", Zhang et al. (2016) developed a method for selecting IPD contractors. Using this system, all IPD stakeholders rate the transactive memory of others across three main factors: specialization, credibility, and coordination, and the appropriate combination of IPD parties is evaluated using social network analysis (SNA). This technique is a relational-based framework that considers trust and collaboration, being factors integral to IPD. Nevertheless, a strict prerequisite to its adoption is that project participants possess previous, shared memories or experiences of cooperation, which limits the application of the framework. Accordingly, there remains a need to propose an objective MCDM framework to evaluate contractors on IPD projects without the limitation of previous relationships between the parties, which is the main contribution of this paper.

CASE STUDY ANALYSIS

The 2012 AIA IPD Case Study Matrix provides detailed project information and firm selection strategies for 12 unique IPD projects (AIA 2012). Figure 1 presents the contractor and/or subcontractor selection processes and methods used in those case studies. Two out of the twelve case studies had no published information on the party selection processes and therefore were excluded.

1 [Cathedral Hill Hospital]

- The Contractor was selected based on (1) familiarity with IPD and lean construction and (2) previous history/relationship with the owner, who was also keen on IPD.
- Subcontractors were pre-qualified, then pre-qualified firms submitted RFP, then shortlisted firms were interviewed. Among the considered criteria for subcontractor selection were (1) experience with IPD and (2) willingness to be part of IPD and (3) willingness to collaborate.

2 [MERCY Master Plan Facility Remodel]

- RFQ were sent to contractors and considered the following criteria: general company information, regional experience, healthcare experience, and IPD knowledge and experience. A scorecard was used to evaluate RFQ to shortlist firms, who were then interviewed on subjects, including: relational aspects of project delivery, budgeting process, and logistical strategies specific to healthcare and IPD environments. The selected contractor had shared project experience with the architect.
- Subcontractors were pre-qualified based on positive past work experience with the contractor. Then pre-qualified firms submitted RFP on experience with IPD, experience with other technologies that would be used on the project, and financial background. Finally, shortlisted firms were interviewed.

3 [Lawrence and Schiller Remodel]

- Contractor selection was based on (1) previous relationship with owner and (2) interest in IPD.
- Subcontractor selection was based on expertise, past experience, and trust.

4 [Edith Green Wendell Wyatt Federal Building]

- Public RFP were sent to contractors inviting them to attend a project workshop. Then, 13 contractors met with owner in "Early Exchange Meetings" to discuss project requirements, including project history, design aims, and constraints regarding time, cost, and site. The IPD process was a main topic discussed as applicants were made aware of the necessity to support a collaborative approach. Final contractor selection relied on their qualifications, past performance, key personnel, conceptual cost estimate and pricing for design phase services.

5 [Autodesk Inc.]

- RFP were issued to select an already established team of architect and contractor. The RFP expressed the owner's targets regarding scope, cost, sustainability, and type of agreement. The architect and contractor were selected on the basis of qualifications, understanding of the local market, BIM and LEED experience, and willingness to abide by a "true" IPD agreement.

6 [Sutter Health Fairfield Medical Office Building]

- At the owner's request, the architect met with the contractor to investigate the fit and alignment of their cultures. They met and found it was a good fit. The companies had past experience working together on traditional projects in the Midwest.

7 [Cardinal Glennon Children Hospital]

- The owner decided to adopt IPD after the commencement of the design stage, once the architect, engineer, and contractor were on board. The owner, architect and contractor had previous work experience and relationships.

8 [Encircle Health Ambulatory Care Center]

- Selected the contractor based on (1) the owner's previous experience with the contractor and the (2) the contractor's previous experience with IPD.
- Subcontractor selection was based on price, personnel qualifications, and previous work with the contractor.

9 [Walter Cronkite School of Journalism]

- Public RFQ were issued to select an already established team of architect and contractor, purely based on qualifications. Around 15 responses were received and 3 teams were shortlisted, based on past experience with public entities, familiarity with the type of project, and the prospect of working well together.

10 [USCF Mission Bay Medical Center]

- The owner adopted a best value selection process, developing a questionnaire that allows the selection of contractors based on experience and expertise and not on the lowest price.
- Subcontractor selection followed best value selection based on the quality of experience. The expectations for teams, relative to IPD principles, were listed as part of the bid documents. Criteria were specified to support IPD goals, whereby heavy weight was given to collaborative experience.

Figure 1: Contractor and Subcontractor Selection Processes and Criteria in 12 IPD Case Studies

Analyzing the selection methods on these projects, it is apparent that most projects adopted requirements particular to the IPD procurement route. For instance, on projects 1,2,8, and 10, owners focused on the contractors' knowledge and experience with IPD as a criterion in the selection process. Moreover, on projects 1,3,4, and 5, all bidders were made aware of the IPD form of delivery and contract to be signed and therefore the selected bidder would have expressed their willingness to sign and take part in a "true" IPD agreement. Additionally, on certain projects, bidders' experience with implementing lean (project 1) and Revit/BIM (projects 2 and 5), which are operational principles and systems integral to IPD, were specified. It is worth noting that a recurrent factor adopted across several projects was the previous relationships of the parties, owner, architect, and contractor, be it on IPD or traditional projects (projects 1,2,3,7, and 8). Finally, another unique criterion in selecting contractors for IPD was the contractor's compatibility with the architect and the prospect of positive collaboration between the parties (projects 5,6, and 9). In fact, this is not usually considered in traditional delivery routes but is especially important in IPD in the presence of a multi-party agreement establishing an official relationship between the contractor and the architect and with the requirement for high levels of communication and collaboration between those two parties on IPD projects. From these studies, the authors well able to identify and translate certain factors of importance in contractor selection used in the above IPD projects into IPD-specific criteria to be included in the proposed decision-making tool, as presented in Table 1.

Table 1: Criteria obtained from IPD Case Studies

No	Criterion	Case Study
1	Previous implementation of lean in contractor's organization	1
2	Knowledge and experience with IPD	1-2-8-10
3	Willingness to be part of IPD and sign "true" IPD agreement	1-3-4-5
4	Systems and technologies that are integral to IPD (e.g. BIM, Revit)	2-5
5	Successful previous relationship with owner/architect/contractor	1-2-3-7-8
6	Compatibility of contractor and architect	5-6-9

Notwithstanding, it is apparent that none of the case studies present a comprehensive contractor selection procedure specific to IPD nor an official decision-making tool for choosing the most appropriate contractor based on a scientific method and an inclusive list of criteria. Rather, it would appear that criteria for qualification-based contractor selection in traditional delivery routes were considered, while adding certain requirements related to IPD. Moreover, the majority of the projects adopted an interview process whereby the bidders' compatibility with IPD was assessed, but again without providing the method for evaluating and ranking the bidders. In any case, if any decision-making tool was used, there are no official publications in the literature detailing the basis of the same to advise on the optimum process for IPD contractor selection.

RESULTS AND DISCUSSION

PRESENTATION OF THE IDENTIFIED FACTORS

After conducting the systematic review, a total of 42 factors were identified, filtered, and organized into four categories: Technical Qualifications (14), Past Experience and History (16), Financial Qualifications (5), and IPD Qualifications (7).

PRESENTATION OF FINAL HIERARCHY OF CRITERIA

Subsequently, the 42 identified factors are organized under the four-level hierarchy presented in Figure 2 below.

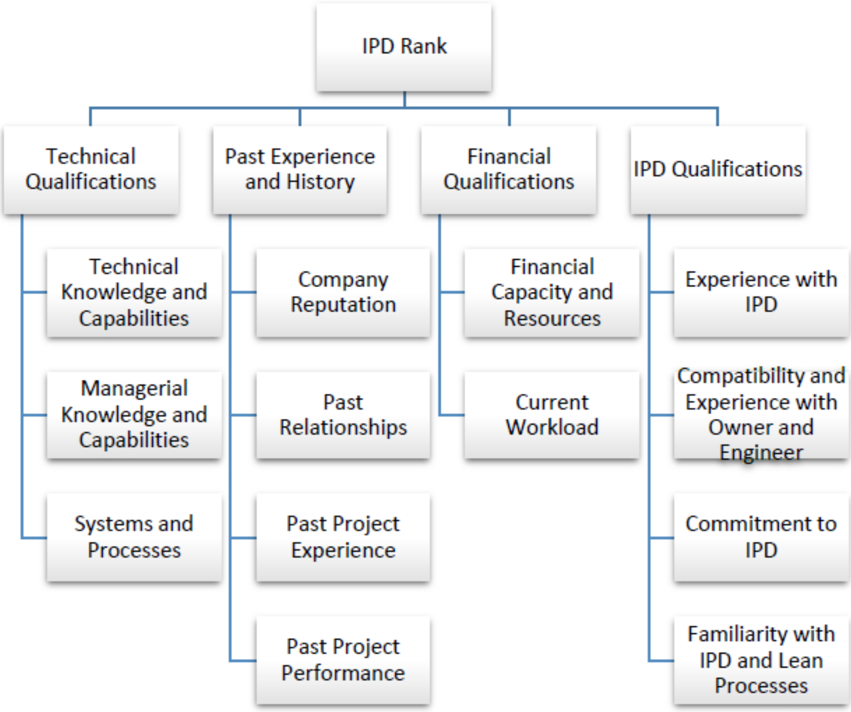

Figure 2: Hierarchy of Factors

PRESENTATION OF THE FUZZY DECISION-MAKING TOOL AND RUBRIC

The development of the fuzzy inference system relies on specifying the inputs and outputs of the model. In this paper, the output is the IPD rank, and the inputs are several factors that contribute to this rank. A membership function must be defined for every factor. After identifying those membership functions, the factors of the lowest level are rated by the user, using the rubric, to identify the final output score, representing the contractor's IPD rank. The forthcoming sections will discuss the developed model in detail.

Using the developed rubric, the users input a rating from '0' to '10' of each lower-level factor, where '0' represents a minimum rating and '10' represents a maximum rating.

Input and Output Factors

The model is a multi-level hierarchy, where the first level in the hierarchy is the major goal itself, the IPD Rank. The second level presents the main categories that contribute to the score of the IPD Rank. Finally, the third level, which is the lowest level, defines the sub-factors.

To use the tool, the following steps are followed: (1) the user inputs the rating of the third-level factors using the developed rubric (2) next, fuzzy calculations are applied in order to obtain the ratings for the level 2 factors, which will be the outputs from the level 3 calculations and (3) finally, the ratings of the level 2 factors are used as input to calculate the rating of the level 1 factor, which represents the IPD rank. As such, this model could be described as an aggregated tree, in which the output of a function is used as an input of another function to get the output of the final goal.

Membership Functions and Rules

After conducting an extensive literature review, the authors implemented the most commonly utilized membership functions: low, medium, and high. Furthermore, the membership functions were represented by trapezoidal and triangular functions, trapezoidal functions for both low and high membership functions and the triangular function for the medium membership functions. Fuzzy logic allows the overlapping between different functions so that each score/rating might be represented by membership in two functions, which is the core benefit behind choosing this method. The parameters of the membership functions have been set with the following values, representing the span of the functions, low [0 0 2 4], medium [2 5 8], and high [6 9 10 10].

The subsequent step is identifying the different scenarios, or rules, that might occur in evaluating the output. The number of different scenarios is based on the number of factors and the number of membership functions. So, in the case of a category that has 4 sub-factors, each having 3 membership functions, the total number of rules required is MF^SF (i.e., 4^3=64 rules). Overall, 227 rules were defined for the entire model.

CONCLUSION AND FUTURE RESEARCH

This research provides a practical tool for owners to select the most suitable contractor for an IPD project. This research adds to the body of knowledge by providing a metric to the decision maker so that he/she can have a better understanding of the requirements for contractor selection in IPD to optimize successful project outcomes. The developed framework facilitates the selection of the appropriate contractor for the IPD project at hand, considering a rounded classification of criteria along IPD-specific requirements. The benefit of the tool is in its flexibility, as it is suitable for use on any project since its main membership functions and rules can be adjusted as required using the input of project stakeholders. Nevertheless, it was apparent from the investigated IPD case studies that an interview process is essential, whereby the owner and the architect met with the bidders to assess several qualitative factors such as the "willingness to collaborate", "team chemistry" and the "compatibility of the cultures". Therefore, the authors suggest that this tool be used not as a replacement but rather to supplement the interview process. For instance, one potential application is applying the tool as a pre-qualification step to filter contractors prior to the interview process. For future work, a more comprehensive model can be developed that considers additional factors, which would benefit from the input of construction professionals in validating the identified factors and contributing to the development of new factors. Another opportunity is the framework's application to a case study after calibrating the membership functions and rules through input gathered from project stakeholders and experts.

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LIFE CYCLE COST AND VALUE OF NORWEGIAN SPORTS FACILITIES

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ABSTRACT

Sports facilities are built to create value for owners and users. In the front end, it is crucial to make decisions based on information about the Life Cycle Cost (LCC) and the possible benefits of the facility. This paper aims to create knowledge about the relationship between the value and LCC of sports facilities. This has been done through literature review, document studies, and workshops.

The construction costs have been compared to the operation and maintenance (OM) costs for 11 sports halls. The results show a ratio between OM and construction costs between 0,1 and 3,7. Diverse aspects could explain this, such as the lack of a standard model for what to include in the OM costs and volunteer work with planning, and OM not counted.

Planning in sports facilities construction often relies on volunteers from the sports clubs, leading to a lack of competence and resources to implement value-centered approaches like the Lean Construction methodology. This paper shows that it is challenging to quantify the value generated by sports facilities, and value is highly dependent on perspective. There is a need for a more systematic way to evaluate the OM cost and the value generated by the sports facilities.

KEYWORDS

Life cycle cost, value generation, lean construction, sports facilities

INTRODUCTION

Projects are generated to create value for owners and users. Diverse types of buildings will contribute to value in various ways. When deciding to start a project, the value and cost must be considered (Ballard & Morris, 2010). In the front end, estimated costs for planning and constructing a facility are often based on the cost of previous projects (Barakchi et al., 2017). Operation and Maintenance (OM) costs should also be considered in the big decisions during the front-end phase. As decision basis for the final decision to finance a project, it is crucial to estimate the Life Cycle Cost (LCC) of the facility, comprising the planning and construction costs, cost of operation and management of the facility, and operation cost of the activity at the facility (e.g., cost of running the hospital activity) (Evans et al., 2004). The LCC, together with an estimate of the value created by the activity in the facility, is important to make the right decision. Life-cycle costs comprise all the expenses incurred during the lifetime of the product, work, or service to have an overview of the complete cost picture.

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Sylte et al. (2017) assessed factors affecting the investment cost of a sports hall and created awareness about these factors to help the future implementation of sports halls. Little research has been found about the size of facility management costs and the relationship between construction costs and operation and maintenance costs. Research shows that due to the gain in health effects, the benefits of sports facilities are three times the construction costs (Strøm et al., 2022). Compared to general building projects, some additional aspects that need to be addressed when constructing sports facilities are under consideration. This includes concerns about a country's vision and objectives for sports and activity in society. However, sports involve a vast pool of conflicting perspectives and stakeholders, e.g., different sports federations, sports clubs, varying levels of knowledge, resources, and financial strength. The different perspectives affect the perception of value and the motivation for value delivery. Also, there is often some amount of voluntary work related to the planning and constructing of sports facilities. So, what reflections do you need to do to create value at sports facilities?

This research aims to elucidate and increase our knowledge about the relationship between sports facilities' construction costs, operation and maintenance costs, and the value generated by them. The following research questions are defined:

- RQ 1: How do the construction costs correlate with the operation and maintenance costs in sports facilities?
- RQ 2: What are vital value considerations when constructing a sports facility?

The study is limited to Norwegian sports facilities. In Norway, many sports facilities are built, with a total building cost of about 500 million USD per year (Sylte et al., 2017). Gaming funds, which is profit from the National Lottery of Norway, partly fund the facilities. The Norwegian government owns the National Lottery, and the gaming funds are distributed by the Norwegian Ministry of Culture and Equality (Norwegian Ministry of Culture and Equality, 2022). The average funding from gaming funds is around 20%. The rest is financed by the municipality, the sports club, sponsors, etc.

METHOD

To answer the research questions, we conducted a literature and document study. In addition, we participated in a workshop organized by the Norwegian Olympic and Paralympic Committee and Confederation of Sports (NIF), where all the sports federations in Norway were represented. In the literature study, we used the databases Oria (Norwegian University of Science and Technology's online university library) and Google Scholar, searching for combinations of "cost, "Life Cycle Cost," "value/benefits," and "sports facilities." Not much relevant literature was found covering the cost, LCC, or value of sports facilities, but we found some literature covering other types of facilities. We reviewed the top 50 hits in the searches to identify relevant literature sources.

The data in the document study is collected from the Norwegian web page www.godeidrettsanlegg.no (Gode idrettsanlegg, 2023). "Gode idrettsanlegg" (GIA) can be translated to "Excellent Sports Facilities." The Centre for Sports Facilities and Technology (SIAT) at the Norwegian University of Science and Technology (NTNU), NIF, and the Norwegian Ministry of Culture and Equality finance this web page. Its purpose is to contribute to high-quality sports facilities' building and operation. The web page intends to publish articles, news, information about sports facilities, and tools and guides for successful sports facilities. Notably, "Excellent Sports Facilities" also publishes and presents model sports facilities (MSF). These MSFs are facilities that stand out as exemplary, for instance, in terms of cost, effectiveness, use, innovation, or cooperation between sports. The MSFs are recommended to GIA by the national sports federations to ensure that the best sports facilities from the different sports become MSFs.

Among the data obtained about the MSFs are the construction cost, the operation and maintenance cost, and the facility area. As a result, GIA holds cost data for many MSFs.

PROCESSING OF DATA

The study has investigated the indoor sports hall facility category, as this category receives most government funding through gaming funds (Norwegian Ministry of Culture and Equality, 2021). The MSFs included in this study are categorized as indoor sports halls by GIA. When conducting this study, we have not further assessed which MSFs can be classified as indoor sports halls. As an example, gymnastics facilities are not counted as indoor sports halls, while indoor sports halls containing gymnastics facilities, among other facilities, are included.

GIA does not obtain information about when the model sports facilities were completed during the completion year, so all construction costs are set to December of the completion year when indexing. This assumption will probably not impact the result significantly, considering the limitations of the data.

The cost data from GIA are given in NOK but are presented in USD for this paper. The exchange rate fluctuates around 10 NOK per USD, so for simplicity, we are using an exchange rate of 1 USD = 10 NOK for all data in this paper.

TOOLS

The collected data were systemized and analyzed in Microsoft Excel. The indexed construction cost is based on Statistics Norway's construction cost index for residential buildings (Statistics Norway, 2023). The chosen index and inputs are considered the most representative.

LIMITATIONS

The collected data has some inconsistency. The information was not easily comparable as different people gathered the information at different times and from various sources. Also, as the data was not initially collected for research purposes, there has been a lack of consistency in how data was gathered. We left out several facilities due to the need for more consistency in the data. However, this ultimately led to more consistent results for comparison.

THEORY

LIFE CYCLE COST IN CONSTRUCTION

A project goes through different stages, from initiation, design, and execution to operation. Project costs are estimated during project planning through these phases (Westkämper et al., 2001). The cost estimates are used as a part of the decision basis at decision gates in the project. Costs related to planning, design, and construction are estimated, often using analog estimation in the early stages of the project (Barakchi et al., 2017). The costs of similar previously built buildings per m2 gross area are often used for estimation.

To make informed project decisions, the focus should be on Life Cycle Costs (LCC), not only construction costs. An LCC calculation considers all costs for a product or service during its life cycle (Miske, 2010). The aim of using LCC is to evaluate the cost-effectiveness of alternative design strategies by considering the potential initial and operational costs incurred over a specified period (Sadliwala & Gogate, 2022). The use of LCC has over 50 years of history and can reasonably estimate the total cost of ownership of construction assets (Sadliwala & Gogate, 2022). Despite its proven utility, successful application and diffusion within the construction domain are scarcely seen (Manewa et al., 2021). According to Sadliwala and Gogate (2022), there needs to be more data available for implementing LCC in construction. Costs of the life cycle should include at least three groups of costs (Miske, 2010): 1) costs for the acquisition of the building, 2) costs for the use of the building, and 3) costs for the deconstruction of the building.

The cost of building procurement includes all planning, design, and construction expenses. The Norwegian standard NS3453 states what costs should be included in a cost estimate for a building (Standard Norge, 2016). Included should be all the costs related to the building, installations (e.g., electrical, HVAC, etc.), outdoor works, general expenses (planning costs, design costs, project management costs), special costs (plot costs, VAT, furniture, etc.), expected additions and project owner reserves. Final costs should count all the costs related to the building according to the NS3453 and will also include the impact of the uncertainties and use of contingencies. For sports facilities, Sylte et al. (2017) show a variation in construction costs for sports halls, where costs depend on the project delivery model, location, project ownership, and whether the sports hall is part of a school project. By monitoring the construction costs of sports halls in Norway, SIAT has discovered that these costs have grown over time (Sylte et al., 2017).

According to the International Facilities Management Association (IFMA), the costs for the use of a building, the *facility management costs*, or operation and maintenance costs (OM) used as an expression in this paper is associated with a maintenance cost, replacement cost, janitorial cost, cost of moves, indirect cost, utility cost, life safety cost, support and project costs (security, space planning, and employee amenities), and financial indicators (lease, fixed assets, and operation, among others) (Islam et al., 2019; IFMA, 2023).

Lee (2012) shows that multiple studies investigated the ratio of relative costs in owning and using a commercial office building. With a construction cost of 1, Evans et al. (2004) found operation and maintenance (OM) costs to be 5 over the lifespan of the building, while Hughes et al. (2004) found the ratio to be 0,4, and Ive (2006) found the ratio to be 1. The business operation costs are shown to be considerably higher, from 200 (Evans et al., 2004), 12 (Hughes et al., 2004), and 15 (Ive, 2006) times the construction costs.

VALUE GENERATION

Values and Value

A value focus is essential in Lean theory. The report from Lauri Koskela from 1992 was, in his effort to conceptualize the Lean production philosophy for construction, one of the first to emphasize how important customer value is in construction projects (Koskela, 1992; as cited in Tillmann & Miron, 2020). In the Transformation-Flow-Value generation (TFV) theory, eliminating non-value-adding activities (waste) is the main principle for the flow view. The value generation view is about creating value for the customer by fulfilling requirements, with the principle of eliminating value loss (achieved value compared with the best possible value) (Koskela, 2000).

There is ambiguity related to the term *value*. Due to the lack of a commonly accepted definition, the concept of value is associated with some confusion. As a response, a comprehensive definition of the value term for a Lean Construction context was presented by Drevland et al. (2018) through nine tenets. In this definition, they maintain that values (plural) and value (singular) differ. Values are essential for guiding someone's evaluative judgment. In contrast, value is the outcome of an evaluative judgment based on knowledge and driven by values. Similarly, Tillmann & Miron (2020, p. 107) state that "values are related to core beliefs, morals, and ideas, while perceived value is related to a judgment of an object by a subject."

Organizational values possess several values that make up a value system. These characteristics make it difficult to isolate for analysis. This contrasts with personal values, which are values possessed at an individual level and are, therefore, easier to isolate (Schwartz, 1992; as cited in Bourne & Jenkins, 2013).

According to Aadland and Askeland (2019), values create the intentional basis for actions, the direction for actions, and the basis for interpretation in evaluating actions. This ultimately means that all actions are based on values. There is a saying that every well-written villain is a hero of their own story (Vogler, 1992). All actions – good or "evil" - are first and foremost based on the practitioner's perspective, who performs actions based on their values.

The core principles of Lean Construction are adapted from production theory. The ultimate goal of LC can be described as generating value for the customer and avoiding non-value-adding activities (i.e., waste) (e.g., Koskela, 2000; Bertelsen, 2001; Tillmann & Miron, 2020). Woodruff (1997) argues that, when generating customer value, one takes the perspective of an organization's customers by delivering a product based on the customer's needs. Projects, however, are complex one-off events characterized by multi-stakeholder environments. Thus, multiple perspectives exist (Tillmann & Miron, 2020). So, who is the customer in a construction project? The term *customer* is closely related to what is referred to as a *stakeholder* in project management literature and may refer to everyone affected by the project, not only the paying customer (Drevland & Tillmann, 2018). Based on the stakeholder typology from Mitchell et al. (1997), Drevland and Tillmann (2018) identify four *definitive* stakeholders, i.e., stakeholders possessing all three stakeholder attributes in a project (power to impose, legitimacy, and urgency): the owner, the designer, the builders, and the society at large.

With the condition that projects are systems for value delivery, Drevland and Tillmann (2018) explore the question of whom value should be delivered to in a project and that the question is a matter of value philosophy. They argue that the key to deciding whose value matters lies in understanding the motivation for the value delivery and identifying three causes for value delivery:

- **Transactional motivation:** Centers around a formal transaction between two or more parties.
- **Selfish motivation:** Any action a party takes to exploit contractual ambiguities, motivated by greed, self-preservation, or interest in maintaining a good relationship or reputation for future business.
- **Altruistic motivation:** Delivering value, not by formal transactions or for egoistic reasons, but for altruistic reasons. Corporate Social Responsibility, for instance.

The definitive stakeholders will always matter, and their motivation is mainly transactional. Value delivery is based on selfish or altruistic motives when going beyond formal contracts and regulatory constraints.

A cost-benefit analysis contributes to a solid, transparent, and comparable decision basis for politicians and other decision-makers when evaluating different concepts (DFØ, 2018)– highlighting the effects of alternative solutions before a decision makes it easier to choose the best solution for society. When performing cost-benefit analyses, the benefits and the costs must be quantified. Not much is written about quantifying the value of the benefits of sports facilities other than by (Strøm et al., 2022). They claim that the health gained from sports facilities is three times the cost.

FINDINGS

CONSTRUCTION COSTS CONCERNING OPERATION COSTS OF SPORTS FACILITIES

The research is based on the facilities presented in Table. The facilities are, as accounted for, indoor sports halls. They generally consist of a multi-purpose court intended for basketball, handball, and volleyball but are also usable for other sports, such as futsal and floorball. Further, some facilities have separate rooms or courts for other sports, such as archery, gymnastics, sport climbing, table tennis, fitness, spinning, dancing, and fencing. In addition, the facilities offer wardrobes, toilets, common areas, spectator stands, conference rooms, and kiosks.

The different projects, their construction cost, operation and maintenance (OM) cost, usable floor area (m^2), and construction cost per m^2 are given in TableTable 1. The construction costs vary from approximately 6 to 47 million USD. The operation and maintenance costs range from about 65 000 to 880 000 USD per year. The construction cost per m^2 is divided by usable floor area, which was found to be the best representative area in a sports hall. The costs for deconstructing the facilities are non-existing and, therefore, not included in the study.

Table 1: Data from the MSFs

Facility Name	Indexed construction cost [USD]	OM cost [USD/year]	Usable floor area [m²]	Construction cost per m² [USD/ m²]
Utleirahallen	9 019 144	265 000	3 580	2 519
Hønefoss Arena	14 192 361	100 000	12 000	1 183
Sjulhustunet	24 164 973	200 000	7 700	3 151
Harestua Arena	16 863 992	210 000	4 700	3 588
Lislebyhallen	15 518 750	64 252	3 460	4 485
Bugårdshallen og Sandefjord bueskytterhall	6 188 621	455 179	8 283	1 238
ROS Arena	8 975 165	230 000	3 500	2 564
Bærum Idrettspark	47 392 620	880 000	16 200	2 925
Hyllestadhallen	6 649 378	70 900	2 880	2 309
Volda Campus SpareBank1 Arena	21 955 921	390 000	11 200	1 960
Glommasvingen skoleanlegg	6 293 162	96 408	2 080	3 026

VALUE IN NORWEGIAN SPORTS

To answer what they value in Norwegian sports, we have done a document study on reports from NIF. The findings we present are valued from the top level in Norwegian sports. However, as there are many sports organizations to satisfy, it must be acknowledged that the wide variety of sports leads to many different perspectives that need to be pleased in the construction of sports facilities. In 2019, NIF collaborated with the sports federations in Norway and committed to a set of goals, strategies, and measures for the future. These decisions were presented in two reports, one for constructing sports facilities (NIF, 2019a) and one for sports policies (NIF, 2019b). The reports represent a shared understanding and agreement on which direction sports policies and sports facility construction should take in Norway. The intention was to agree on a set of goals, strategies, and measures to guide the sports federations when they make their own strategic decisions. NIF aims to work for equal opportunities for all to perform sports after their own needs and desires without being victims of unreasonable discrimination (NIF, 2019b). A strategy for achieving this purpose is presented with a vision, business idea, strategic efforts, overall objectives, and fundamental choices. These are given below.

- **Vision** – "Sporting joy for all."
- **Mission** – "Everyone should experience sports, coping, and development in the safe and sound sporting community."
- **Strategic efforts** – A set of strategic priorities for the coming years.

  - Lifelong sports – work for an inclusive and diverse community with outstanding quality to facilitate everyone to be a part of a sports community for as long as they want to.
  - Better sports teams – work for democratic, open, and honest organizations, where voluntary work, which is at the core of many sports teams, should be experienced as a safe and meaningful community.
  - More and better sports facilities – build sports facilities where desired activities can be performed. More predictable economics and environmental efforts during the whole life cycle of a sports facility.
  - Better elite sports – Norway should have world-class athletes and teams. More efforts in helping young talents reach the highest levels.
- **Overall objectives –** "Get more people involved – for longer" and "More new medals."
- **Fundamental choices –** A set of organization- and activity values to guide and improve the sports' work in the coming years.
  - Playful – A sports community where playful curiosity is not neglected.
  - Ambitious – Ambitions about development in sports and organizations for a better society.
  - Honest – Fair play. E.g., no cheating, corruption, or drug use, and equal competition conditions.
  - Inclusive – A community where everyone is seen, feels safe and cares for each other. A community where everyone feels joy and can participate on their level. Everyone is worth the same.

The overall intention for Norwegian sports is to make society better. Thus, it cannot be isolated from the society it is a part of (NIF, 2019b). This means facilitating activities in sports federations but also activities outside the federations' core affairs. In summary, the intention is to create a physically active society with a community sharing excellent sports values. Integrating the sustainability goals from United Nations (2023) is an essential part of this strategy. In collaboration with the sports federations, NIF launched a sustainability strategy based on the UN sustainability goals (NIF, 2023). They decided on five prioritized focus areas anchored in the abovementioned goals, strategies, and measures. The focus areas and associated sustainability goals are presented below:

1. Lifelong sporting joy and healthy sports (SG 3 – Good health and well-being)
2. Inclusiveness, diversity, and equality in sports (SG 5 – Gender equality & SG 10 – Reduced inequalities)
3. Ethical and forward-looking development (SG 17 – Partnerships for the goals)
4. Responsible use of resources (SG 12 – Responsible consumption and production & SG 13 – Climate action)
5. Green sports facilities (SG 12 – Responsible consumption and production & SG 13 – Climate action)

DISCUSSION

The first research question was, "How do the construction costs correlate with the operating expenses in sports facilities?". The construction costs in the study vary from 1200 USD/m^2 usable floor area to 4 500 USD/m^2. We see that still considering sports halls for similar activities, the costs vary a lot. This was also shown by (Sylte et al., 2017), who explained these variations by different project delivery systems, location, project ownership, and whether the sports hall is part of a school project. What is included in the construction costs is well defined by the Norwegian Standard (NS3453), but this standard is not consistently used when cost information is provided. This may impact the findings. For instance, it varies whether buying the plot is included (sometimes the plot is given by the municipality for free), and the amount of outdoor work varies. The same goes for the ground conditions. Further, the degree of precision and rounding differs between different MSF cost data. Lastly, as construction costs lack dating, we assumed that the cost is the final cost for the project owner at completion.

When it comes to the correlation between the operation and maintenance costs (OM) and the construction costs, the results are presented in Figure 1. Figure 1 displays a correlation between the construction and the OM costs but also offers a considerable variation in annual operation costs vs. construction costs. Through previous research, Lee (2012) shows that total OM costs over the lifespan of a building compared to the construction costs vary from 0,4 to 5 times the construction cost. Using a lifespan of 50 years and a discount rate of 4 % (DFØ, 2018), the average ratio of OM costs compared to construction costs is 0,4. The ratio varies from 0,1 to 1,6. Considering without discount rate, the average ratio of OM costs compared to construction costs is 1,0, from 0,2 to 3,7. We see a lower ratio of OM compared to construction costs for some of the sports halls than the findings in Lee (2012). However, we can see findings at the same level, depending on the assumptions used to calculate the ratio. One explanation for the variations could be that it is not very well defined for sports halls what to include in the operation and maintenance costs. For instance, OM cost may be given for the specific part or the whole facility.

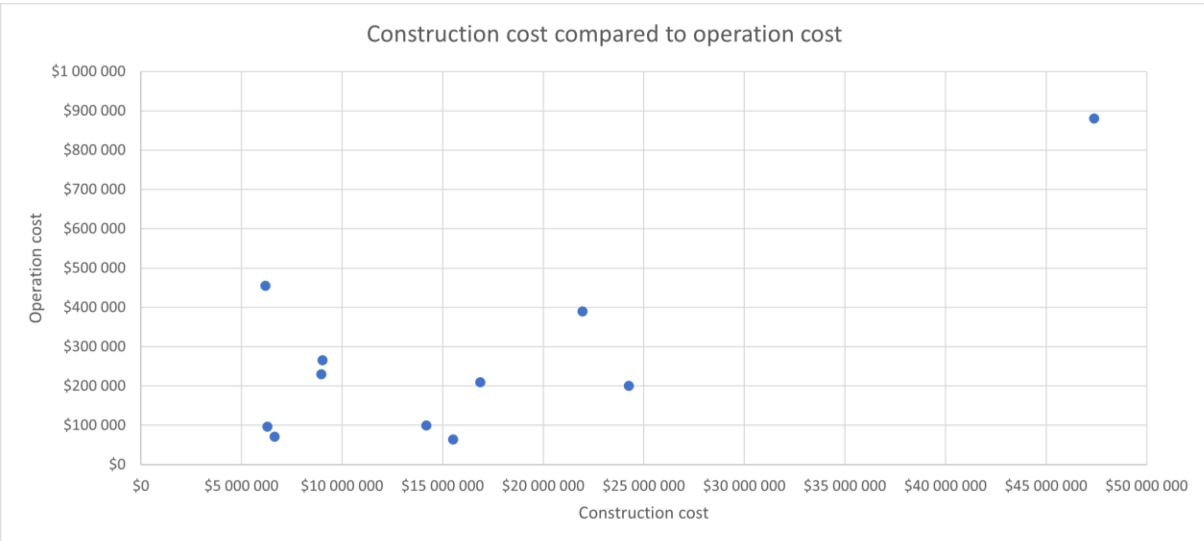

Figure 1: Construction Cost Compared to Operation and Maintenance Cost.

Furthermore, OM cost may be given with or without interest and amortization, value-added tax, or insurance. The complexity of the OM costs is also increased because many sports facilities are operated and maintained partly by the municipality and partly by the sports club. As a result, the OM costs are spread over multiple budgets, decreasing the probability of correct amounts being provided to GIA. The International Facilities Management Association (IFMA, 2023) has defined what to include in facility management costs, where the following should be included; maintenance, replacements, janitorial, cost of moves, indirect cost, utility cost, life safety cost, support and project costs, and financial costs. More unity should be implemented in sports halls regarding what to include in the OM costs.

The motivation for value generation in sports facilities depends on the perspective. Even though the sports federations cooperated with NIF to create a set of overall goals, strategies, and measures, as well as a plan for sustainable efforts, their different perspectives will affect their perception of value. Thus, the motivation for value delivery is effectively affected.

Transactional motivation: The Norwegian Olympic and Paralympic Committee and Confederation of Sports is Norway's largest voluntary organization (NIF, 2019b). Voluntary work is the cornerstone of Norwegian sports and hereby of planning, constructing, and operating sports facilities. The sports club must rely heavily on volunteers to get the work done, especially during planning and operating the facility. Sometimes also during construction, but professional contractors most often do construction with a contract with the actual municipality or sports club. Often the sports clubs manage the project execution themselves, as they are the facility owners. Consequently, this leads to variations in knowledge and experience in planning, design, and construction, depending on whether a person with construction competence is privately volunteering for a particular club. Some municipalities offer free use of the sports halls for the sports clubs; some sports clubs need to pay. An important observation is that not paying for the construction will influence users' or clubs' relations to requirements and cost.

Selfish motivation: The value delivered in sports facilities depends on the stakeholder perspective – any sports federation like to see its sport lifted to appease current members and attract new members. Sports federations might, for instance, compete for governmental funding to build a sports facility or to optimize a shared sports facility for their sport. They might have contrasting perceptions of how the space is best utilized. This can lead to one of the federations exploiting an unclear situation to generate value for their activity at the expense of other sports or activities. In those cases, the sports federation does not necessarily have bad intentions but rather a selfish motivation for value delivery. Still, such an opportunistic value approach might neglect an opportunity for a more holistic approach that could generate more value for the overall purpose of Norwegian sports, as stated in the vision and strategies from NIF.

Another question that needs answering is if mass sports or elite sports are prioritized at the sports facility. Mass sports and elite sports may have conflicting perspectives. Some sports teams have athletes competing at both the elite level and amateur or mass sports level. The Norwegian football club Rosenborg, playing at an elite level, used known Lean principles to create value for the local community. They assisted local football clubs at the mass sports level with funding and competence, intending to help them develop the next local superstar to play for Rosenborg (Malvik, 2022). In this case, the end goal shows signs of selfish motivation. However, the cause was also charitable. Value for elite sports clubs like Rosenborg is usually to win trophies and entertain the local community, which is easier to achieve by using talented (local) players. Moreover, the value of local sports clubs is to facilitate higher participation and be an arena for development and growth.

Altruistic motivation: As mentioned above, NIF is Norway's largest voluntary organization. There is much altruism tied to this voluntarism. Planning and construction of sports facilities often depend on club members or other interested people's voluntary spirit. In Norway, this is most visible on the mass sports level through sports club members or parents of members selling cake or toilet paper. However, it can also be seen at the elite sport level. For instance, supporters make supporter effects (tifos, mosaics, flags, etc.) or songs for their teams' home matches. One extreme example of voluntary work in elite sport is the German football club Union Berlin's supporters, who spent their free time and holidays working on a new modern stadium after the German Football Federation (DFB) threatened to close their old stadium for not meeting the security requirements. In total, 1600 volunteers put in an estimated 90 000 hours of work to save the club 2 million euros in construction costs (Hessler, 2009). The close-knit sports community fortified the already unique supporter culture in and around the club. It shows that even the construction of sports facilities can bring value to society through shared altruism and voluntary work.

Besides comprehensive efforts from NIF to facilitate sustainable endeavors in the construction of sports facilities, there is also demands from the government and the general public. Still, projects are not imposed a sustainable strategy, and the actual implementation of a sustainable approach is a matter for the owners of the sports facilities (usually the sports teams). Thus, the effort put into sustainability is tied to altruistic motivation. Generating value for the user is an elementary component of a sustainable strategy (Malvik et al., 2021). Therefore, a sustainability strategy is inevitably interrelated with value generation. One should ensure that the sports facility covers the needs and requirements put forward by the user and is aligned with the values NIF presents in its vision and strategies.

Strøm et al. (2022) show that the benefits of sports facilities are three times the investment costs, where health effects are counted. We have shown that sports facilities give different types of value or benefits. To do a quantitative cost-benefit analysis, we need to be able to quantify the facilities' value or benefit. The values pointed out above are not easily quantifiable. This is a central challenge when identifying the ratio between sports facilities' value and LCC.

CONCLUSION

This research is aimed to increase the knowledge about the relationship between the Life Cycle Cost of sports facilities and the value the facilities generate. We have investigated the relationship between construction costs, operation and maintenance costs, and value generated by the sports facilities by looking at sports halls.

Regarding the cost of sports halls, both the construction cost and the operation and maintenance costs vary greatly. Also, the ratio between the OM costs over the lifespan of the buildings and the construction costs varies from 0,1 to 3,7, depending on assumptions in the model. How to calculate the construction costs follow a Norwegian standard, while what to include in the OM cost is not standardized. A standard for what to include in OM cost needs to be developed. When much of the work in sports facilities is done by volunteers, it will still be unclear how to count it in a model elucidating LCC.

Diverse types of value are discussed regarding the value the sports facilities generate. A vital issue is that it is not easy to quantify the value generated by a sports facility. The value depends on your perspective if you are the owner, designer, builder, or the society at large. For sports facilities, the owner is most often the sports clubs or the municipality. Transactional motivation is, of course, necessary for the municipality or the sports club due to what often is limited funding. But stakeholders in sports clubs are highly driven by selfish motivation. Decisions during planning and construction are much driven by selfish motivation. However, we also see a lot of altruistically motivated actions in work with sports facilities at any level through the immense amount of volunteer work.

Some attempts are made to identify the cost-benefit ratio of sports facilities. However, more defined rules about estimating construction costs, quantifying operation and maintenance costs, and quantifying value must be in place. A recommendation for further work is to make a standard for what to include in the OM costs. Also, methods need to be developed to standardize what value parameters to include and how to quantify them.

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IPD EN FRANCE: IS IT LEGAL?

Emna Attouri[1], Alan Mossman[2], Laetitia Fehlmann[3], Ian Heptinstall[4], and Laure Ducoulombier[5]

ABSTRACT

Normal design and construction creates poor project outcomes and low productivity. Integrated Project Delivery (IPD) was introduced as a response to these and other shortcomings. Despite the advantages this method provides, IPD is not used in France. This paper discusses different interpretations of French procurement legislation and regulations. French procurement legislation is based on the *European Directive 2014/24/EU on public procurement*. Based on the way the Directive is understood in other EU countries this paper suggests that there is no legal reason why IPD cannot be used for both public and private construction in France. Some will doubtless suggest that this needs testing in the courts before they will risk using it. Limitations of this paper are that it is based on the opinion of a single French construction lawyer and observation of what happens in other EU countries. The implications of this paper for public and private sector clients in France are that they can consider using IPD for more complex projects in their portfolio; for practitioners it is a signal that they can start to learn how to deliver projects using IPD and Target Value Delivery (TVD); for francophone scholars there are whole new areas for research.

KEYWORDS

Integrated project delivery, collaborative contracting, legal barriers, habit barriers, system change.

INTRODUCTION

As elsewhere, construction is very important for the French economy. *As elsewhere,* construction in France is dominated by “*normal*” construction procurement using bilateral, transactional and adversarial contracts. *As elsewhere*, this approach to construction procurement does not deliver what customers want (Barbosa et al, 2017; Egan, 1998).

Construction clients want projects delivered on time, on budget with full scope (Mossman & Ramalingam, 2021). As elsewhere, construction clients in France rarely get this level of service from *normal* construction.

Normal construction systematically separates design from production. The construction sector is the only major industrial sector where this still happens. The result is that designers lack good cost information during the design process and frequently produce designs that are difficult to build. This frequently means that designs need to be reworked (de-scoped) to meet the client cost criterion and to make the project more buildable. This separation often creates

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claims, conflicts, mistakes, costly corrections (rework), and delays. As construction projects become more complex, there are increasing schedule and cost pressures and a growing quest for sustainability and quality. These pressures, the fragmentation of the construction sector and the adversarial relationships that flow from the use of *normal* bilateral, transactional and adversarial contracts put the people involved under significant stress.

IPD can address the problems listed above (Ashcraft, 2022). IPD is a relatively recent way to procure construction based on a relational contract. Only construction customers (clients) can choose to procure in this way.

Most adults in France, as elsewhere, have experience of relational contracts (they signed up to one when they got married). Relational contracts for construction have existed since 1992 in UK, since 1997 in Australia and since 2004 in the USA (Mossman, 2023). In France, this type of contract is not widely known in construction, perhaps because of the language differences.

Some people see barriers to the use of IPD. Since research has been done on IPD application elsewhere, the purpose of this paper is to understand what, if any, legal obstacles there are to the use of IPD in France.

Following the method section, this paper introduces IPD and its key elements and then discusses the potential legal barriers to its adoption by French construction customers.

The research question answered in this study is: *Can public and/or private sector construction customers use IPD (relational) contracts to procure construction in France?*

METHOD

The research method used in this paper is a literature review of IPD and its main characteristics. Then, one of the authors, an experienced construction lawyer reviews a representative IPD contract to identify the legal challenges in France. Her opinion is then challenged by other authors with knowledge of the use of relational contracts in other EU countries that have adopted the same EU Directive (EU 2014) in their own legal code and are already using relational contracts for construction. A content analysis of the French legislation was carried out to answer the concerns raised by the construction lawyer.

LITERATURE REVIEW

The use of collaborative/relational contracting to improve the performance of construction type projects came to prominence in the 1990s in the UK process industries. It built on the previous ideas of partnering by incorporating them into a contractual agreement. Known as *project alliancing*, by the early 2000s its use had spread to the public sector in Australia and from there to Finland in the 2010s. The term IPD emerged in the US in the early 2000s during initiatives to address poor project outcomes of *normal* construction methods – they fail to deliver projects to cost, schedule, and quality (Ashcraft, 2022). To overcome these limitations, Will Lichtig created a multiparty agreement, the *Integrated Form of Agreement* (IFoA) (Lichtig, 2006) for Sutter Health. The IFoA requires key delivery partners to pool their proposed profit *at risk*, jointly manage the project through consensus, and use lean processes during design and construction. In 2007, an American Institute of Architects, California Council group named this approach *Integrated Project Delivery* (IPD) (AIA CC 2007). IPD is an approach to agreements and processes for design and construction (Zhang & Chen, 2010).

IPD developed in the US within the Lean Construction community as a holistic approach to both contracting and to delivering projects. This paper is only looking at the narrower procurement/contracting aspects, making IPD the same as *project alliancing*.

IPD is now seen as a method with the potential to revolutionize project delivery. While *normal* delivery methods are based on transactional contracts, IPD is generally based on a single relational contract. "*Relational*" because consideration is given to the quality of relationships and processes, not just to the end product (Roy et al., 2018). It is a project delivery approach that integrates people, systems, business structures and practices into an innovative process that collaboratively harnesses the talents and insights of all participants to reduce waste and optimize efficiency through all phases of design, fabrication, and construction (AIA CC 2014).

Different organizations approach IPD differently. There are, however, consistent similarities that have been found within most IPD projects and definitions. At core, an integrated team jointly develops project targets, makes decisions by mutual consensus and shares the risks and rewards for achieving them (Azhar et al., 2014).

IPD uses relational contracts — ideally a single agreement that all key participants sign including, at least, the client, lead designer and lead builder. Specialist trades and specialist designers are often added to the contract when they are in a position to significantly affect the project outcome. Use of these relational contracts is common in Australia, New Zealand, the US (Gokhale, 2011) and more recently in Canada and Finland. Clients in other countries are catching on.

For this paper, we use the elements of IPD defined by Rubel and his colleagues from The American Institute of Architects California Council in the second AIA CC report on IPD (AIA CC, 2014). These are listed in Table 1.

Table 1: Main elements of IPD (AIA CC 2014)

Structural elements		**Behavioural elements**
Business model	**Contract structure**	**Enabling behaviours**
Profit separated from cost	Early involvement of key participants	Optimize the whole, not the parts
Costs guaranteed to completion	Jointly developed and validated targets/goals	Trust
Limited entitlement to change orders	Shared risk/reward, based on project outcomes	Integration of information, people, and systems
Profit based on agreed project outcomes	Joint project control and decision-making	Continuous improvement/ learning
	Reduced liability among risk/ reward members	Appropriate use of technology
		Collaboration

Different definitions and widely varying approaches and sophistication levels mean that the term "IPD" is used to describe different contract arrangements and team processes (Kent and Becerik-Gerber, 2010). Other characteristics of IPD are mentioned in other studies. For example, Cohen (2010) mentions the use of a multiparty contract and collaborative decision making. Others write about the use of Target Value Delivery (TVD) and designing to cost. Table shows the frequency of each characteristic observed in different studies defining the delivery method reviewed by Barutha (2018).

Table 2: Literature review of commercial IPD characteristics listed (Barutha, 2018)

	(Kent & Becerik-Gerber, 2010)	**(Ashcraft, 2012)**	**(NASFA, 2010)**	**(Lahdenperä, 2012)**	**(Cohen, 2010)**
Early involvement of key participants	x	x	x	x	x
Shared risk and reward	x	x	x	x	x
Collaborative decision making and control		x	x	x	x

Jointly developed and validated targets		x	x	x	x
Liability waivers among key participants		x	x	x	x
Multi-party agreement	x			x	x

Both Tables 1 and 2 reflect IPD's origins in the lean construction community in the US. Lean methods are integrated into the contracts and/or the execution strategies.

IPD is designed to increase collaboration, align the interests of different stakeholders, and encourage actions that add value to the project. It uses a relational structure with shared risk and reward to create a system that enables and supports collaboration. Delivery partners are generally bound together with a multiparty agreement that includes at least the client, the lead designer, and the lead builder. Key consultants and trades can also be included in the agreement (Fischer et al., 2017). An IPD agreement places authority within the team (which includes the client). Projects are jointly managed so that shared risk is balanced with joint production control so that work is more likely to flow. IPD requires jointly made and validated decisions which enable the team to stay aligned to the project targets. It generally limits liability among delivery partners which enables them to share information in a secure way. In contrast, *normal* construction agreements are made independently between two parties at a time and focus on transferring risks. It discourages behaviours that create value for the client but are not required (or rewarded) by the contract, and results in siloed working, protective and defensive behaviour, keeping information close.

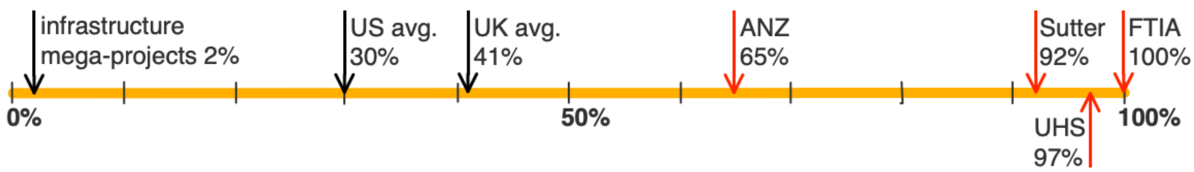

Figure 1: Percentage of projects delivered on-time *and* on-budget. All the projects at the right-hand end – ANZ, Sutter, UHS and FTIA – are IPD or *project alliances*. *Sources*[6]

As Figure 1 and Ashcraft (2022, Table 2) demonstrate, IPD has shown a positive effect on cost, schedule, quality and team morale; researchers have shown IPD projects to be significantly less expensive than Construction Management at Risk and Design-Build comparisons; others found significantly higher satisfaction with IPD on cost, schedule, and quality than other delivery systems; 86% of IPD projects reported an increase in the profit pool as performance exceeded initial expectations; pair-wise studies found that IPD is statistically superior in some aspects, although the specific benefits differed among studies (though some dispute this finding); in other research, IPD projects outscored other project delivery systems and a model using characteristics correlated with project success has predicted better outcomes using IPD for complex projects (Ashcraft, 2022; Cheng et al., 2015; Walker, Harley and Mills 2015).

Though IPD is not yet widely used, it is known as an efficient construction project delivery method. A study, led by Kent and Becerik-Gerber (2010), surveyed several owners, contractors

[6] **infrastructure mega-projects**: on time *or* on budget – Companies public annual report; HIS Herold Global Projects Database, press release 19 Nov 2013 widely quoted; **USA avg**: Construction Industry Institute 2012 Sample of 957 projects avg. US$65m; **UK Avg:** calculated from 2020 Glenigan data for all Non–Housing Construction; **ANZ**: 61 Australian and New Zealand Alliance Projects, 85% on- or below budget, 76% on-time or better, limited use of *lean* thinking. (Walker, Harley and Mills 2015); **Sutter**: 24 projects 2007-19 worth $4.7bn. Overall, 5% under budget with no scope compromises; **UHS** (United Healthcare Services)**:** 40 IPD Projects completed 2007-14 in USA, US$2m-150m (Seed 2014); **FTIA** (Finnish Transportation Infrastructure Agency)**:** 10 IPD projects 2011-22 avg. value €81m.

and designers and revealed that fewer change orders, cost savings, and shorter schedules were listed as the most beneficial aspects of IPD compared to other delivery methods. In addition, case studies of completed IPD projects show the successes realized by project stakeholders.

Companies in the French construction sector are now waking up to the possibility that IPD can help to align the interests of clients, designers and constructors and simulate the collaboration and litigation free characteristics of a single organization (Thomsen et al, 2009).

IPD incentivises delivery partners to collaborate and look out for the interests and success of both the project and of other delivery partners.

KEY ELEMENTS OF IPD

For most people in the construction sector, there is no clear understanding of what's involved in IPD (Kent and Becerik-Gerber, 2010). That is still the case. The following section is a short brief for those not familiar with it.

SELECTING DELIVERY PARTNERS

Construction clients select their delivery partners for IPD projects in a variety of ways.

In the private sector it is not uncommon for the client to select either the designer or the constructor first, to agree the profit that organisation wishes to make on the project and then for the two of them to identify a lead constructor or designer that they can work with and agree with that organisation the profit they want to earn from the project. This snowball type process continues until all the key delivery partners are selected. Key delivery partners are those that can seriously affect the success or failure of the project. This method is not generally possible in the public sector unless it is associated with appropriate open competition.

In the French public sector, as in most parts of the world, it is necessary to organise an open competition where the selection criteria are known from the outset – in Europe they are included in the advertisement published in OJEU, the Official Journal of the European Union. This is the first step in the procurement process.

Finnish public sector IPD projects are procured in this way using a model developed with and for public sector clients in Australia (Ross, 2003) and selection is usually based 60% on quality criteria and 40% on cost. The cost assessment uses the amount of profit that the bidder wants to make from the project and the schedule of rates that they will use to recover their direct production costs and project related overhead during both design and construction. The Finns are clear that having the right people in the project team is vital. They recognise that at the start they don't know exactly what they want to do. According to Finnish construction lawyer, Juha Virolainen, they work to select the *people* who can create the most advantageous project. When selecting partner companies, they are most interested in the people who will represent that company, their IPD experience, their relevant construction experience and their professional skills. "We [assess] skills with case examples or questions. Only named key personnel can participate in these workshops, case examples and *exams*, so the company's best writers cannot answer for them" (personal interview & email with one of the authors).

Finnish procurement law is based on European Directive 2014/24/EU on public procurement (EU 2014) and, as Virolainen pointed out, there is no requirement in the directive for the whole project cost to be known in order to make a selection[7]. French procurement law is based on the same directive. If the Finnish public sector is allowed to procure in this way, why shouldn't French public sector clients be allowed to operate in this way too?

[7] As one author of this paper has pointed out, in 'normal' construction the acceptance of the lowest bid does not mean that the final cost is known at the time of selection either. As noted above, the successful bidder is likely to be looking for opportunities for change orders and claims to increase both the cost and the profit on the project.

AGREEING COST

In *normal* construction the customer pays the contractual price for the work (the agreed tender price + any agreed or awarded claims). This generally means that doing more work creates a bigger profit for the constructors. This leads constructors to bid low and increase the cost during the project at every opportunity through change orders and claims. Once in contract, the actual cost is generally irrelevant!

IPD projects use *target costing*. Target costing shifts production cost from a fixed to a variable amount with profit and market price established upfront (Tillmann et al., 2017). If delivery partners reduce the amount they spend on staff time, materials, etc., (their production costs) their profit increases. This incentive aligns the interests of the designers and constructors with those of the customer (to build a project that meets the requirements of the customer and end-users within their budget). This helps the customer have greater cost certainty while enabling the delivery team to increase their margins.

Many IPD projects include Key Performance Indicators/Key Result Areas (KPI/KRA) that affect the size of the incentive/profit pool.

Normal construction:

Price = Agreed tender price (incl profit) + agreed/awarded claims

IPD Target Costing:

Profit = % of ((Agreed Cost – Actual Cost of work) + KPI/KRA ±bonuses)

Before starting an IPD procurement process the construction client prepares a business case for the facility they are considering. The business case includes information about the economic and other benefits to the client organisation of the proposed facility as well as a review of how much the organisation is willing to pay to acquire those benefits. Once the business case is clear, the client goes to the market to find delivery partners with whom they can work to deliver the facility. Delivery partners are chosen using several criteria which generally include a schedule of rates for members of staff and the profit they expect to earn from the project if it is successful.

Once the key delivery partners are selected and they agree the basic principles of the IPD contract, it is possible to move to the next phase – getting agreement about how much it is likely to cost to deliver the full scope requested by the client within the client's timeframe. This cost – the *Target Cost* – is agreed in a process called *Validation* (Grau et al., 2021). Additional delivery partners may be added to the relational contract during this process as they are identified and selected. The conceptual estimates of cost are made by the constructors who are expected to deliver the project to the price they have estimated.

The delivery team then designs both the facility and the delivery system so that the scope requested by the client is delivered within the time and agreed Target Cost using the Target Value Design (TVD) process (Tillmann et al., 2017). Using TVD requires the delivery partners to design to cost. The estimated future cost is calculated on a regular basis, generally twice a month, so that the delivery team are quickly able to see the effect of their decisions on the anticipated profit that they will make.

How Are Delivery Partners Paid for Their Work?

Delivery partner		*profit ++*	*proportion*
Designer	D	75,000	10.73%
Builder	B	205,000	29.33%
Structural Eng	S	15,000	2.15%
Services Eng	S	20,000	2.86%
Mechanical	M	55,000	7.87%
Electrical	E	38,000	5.44%
Plumbing	P	27,000	3.86%
Groundworker	G	42,000	6.01%
Security	S	15,000	2.15%
Mechanical C	MC	120,000	17.17%
Electrical C	EC	87,000	12.45%
	total	**699,000**	100%

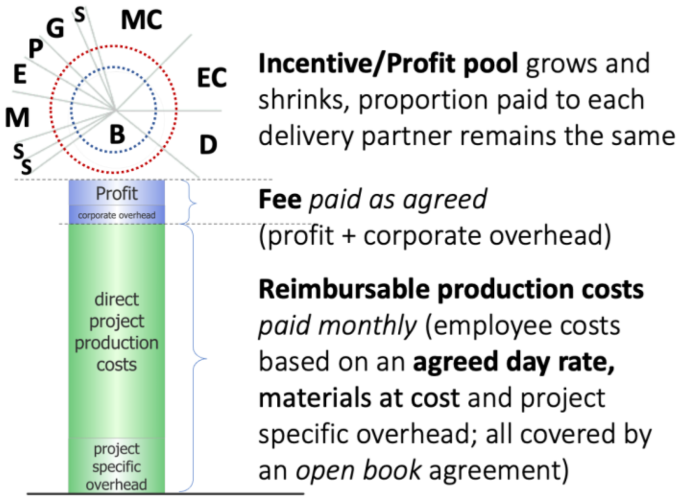

Figure 2: How do delivery partners get paid? Project production cost payments and incentive pool (= fee) Source: Mossman with permission; image derived from Ross (2003), Wilson (2014), Morwood, Scott and Pitcher (2008) and Fischer et al (2017)

Figure 2 shows how much profit the delivery partners to a relational contract have agreed (left hand side). The total is poured into an incentive/profit pool (the fee) and the delivery partners agree that each will receive that percentage from the pool no matter how large or small the pool is at the end of the project. So, the mechanical contractor (MC) for example will receive 17.17% of the profit pool at the end of the project. If the delivery team are successful in keeping the reimbursable costs (green bar) below the total agreed with the customer, some of the saving will be added to the project pool and the remaining saving will go to the customer. The contract may also include additions to – or deductions from – the incentive pools that depend on how well the delivery partners have addressed the client's KRA and/or KPI.

If the reimbursable costs exceed the total agreed with the client, the profit pool related to the project costs will shrink. Most clients recognise that if they wish to retain the project team as *advocates for the project,* they need to ensure that delivery partners do not make a loss. What this means is that the delivery partners may make no profit (the pain), but all their costs will be reimbursed and the customer will pay anything over and above the reimbursable cost plus fee agreed at the start of the project. So far as the authors are aware, this has only happened once.

How Are Payments Agreed?

Figure 3 shows the process flow of a typical IPD project using TVD. Notice that the key project delivery team members are assembled from the beginning (1). They first work together to agree each party's production cost rates, project specific overheads and fee (profit + corporate overhead at risk). Agreement of the contract terms and conditions is the first step in validation (2) – these discussions help to build the team while building a foundation for understanding the business case and the *Conditions of Satisfaction* for the project. The key task in validation is to establish if the project can be delivered within the budget and timescale requested by the customer. If they feel it can be, there are final negotiations on the contract terms and conditions, schedule, the people who will be involved, hours teams will spend in the co-location space, and risk/reward arrangements so that these can be included in the contract.

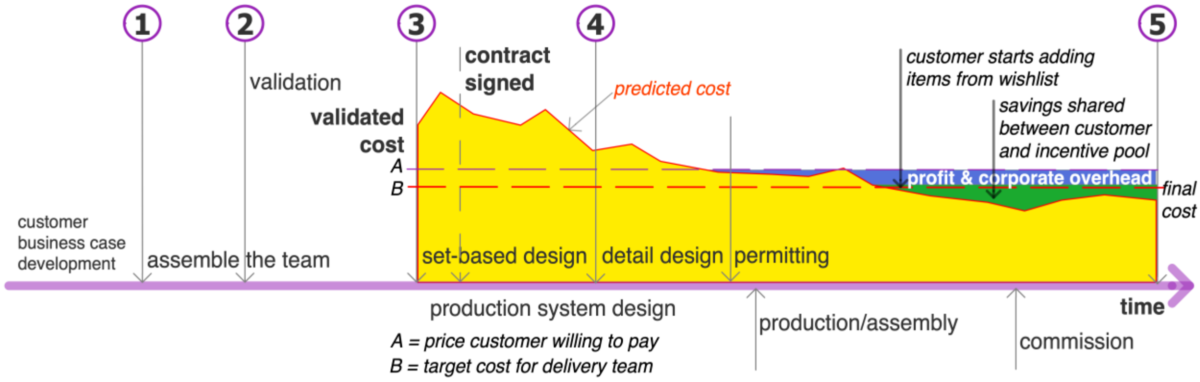

Figure 3: TVD process flow (Mossman with permission)

They work collaboratively from (3) to deliver the project. Project cost is regularly tracked and the total estimated cost is updated every 2 to 4 weeks. Because the constructors are already members of the delivery team, it is they who provide the cost estimates; they have *skin in the game* and is it in their interest to produce the best possible estimate they can. Their estimates may be reviewed by cost consultants. As details of the design become clearer the estimates become more and more accurate and monies that may have been initially allocated to contingency diminish. The predicted cost between (3) and (5) generally falls. At some point the predicted cost generally falls below the total price the customer wants to pay (A) and there is then *some* money in the profit pool to be shared between the delivery partners. When the predicted cost falls below the allowable target cost (B) some of the savings made are added to the incentive/profit pool. Some customers use the savings that they receive to buy additional scope from their *Wish List*. This additional scope adds to the funds in the profit pool.

ARE THERE LEGAL BARRIERS TO USING IPD IN FRANCE?

In this section, potential legal barriers to implement IPD in France are presented for both public and private sector based on the contract review done by one of the authors, a construction lawyer.

There are no legal obstacles to the private sector using IPD.

The principles on which an IPD contract is based (payment terms, limitation of builder and designer liability, early termination of contract) do not contravene the rules of public policy applicable to private contracts under French law.

The Public Procurement Code (*Code de la Commande Publique*, "the Code") requires, with some exceptions, the use of competitive procedures for the award of a public contract. Article L.2152-7 of the Code requires the contracting authority to award the contract to the tenderer who has "*submitted **the most economically advantageous tender"*** on the basis of one or more precise objectives linked to the subject of the contract or its performance conditions.

Art. R.2152-7 states: "*In order to award the contract to the tenderer or, where applicable, to the tenderers who have submitted the most economically advantageous tender, the purchaser shall base himself either 1) on a single criterion which may be (a) the price, provided that the sole object of the contract is the purchase of standardised services or supplies whose quality cannot be varied from one operator to another (b) The cost determined according to an overall approach which may be based on the life cycle cost defined in Article R. 2152-9. Or 2) on a number of non-discriminatory criteria linked to the subject-matter of the contract or its performance conditions, including the cost criterion and one or more other criteria including qualitative, environmental, or social aspects*. [...] " (Légifrance, 2023)

It follows from the above that the cost criterion must necessarily be considered for the award of a public contract. This criterion is important, but it rarely represents more than 50% of the overall assessment score. The notions of "price" and "cost" are not defined in the Code. Almost all public design and build contracts are awarded based on a global and, often, fixed price.

On the day an IPD contract is signed, the programme has not been decided and the overall price is neither determined nor determinable. These elements are defined by mutual agreement between the delivery partners during the *validation* phase and become part of the contract during the early part of the design phase provided the total price is within the client's budget.

The only financial information generally communicated to, and agreed with, the client by delivery partners prior to the start of the validation phase is the hourly or daily rates for the people who will do the work and the amount of profit and corporate overhead (the **fee** in Figure 2) to be earned if the project is delivered successfully.

RESULTS AND DISCUSSION

There appears to be no legal barrier to the private sector using relational procurement in France. The private sector is not subject to the Code. Private clients have the option to a) Negotiate with delivery partners that it has chosen and conclude a contract by mutual agreement, or b) Set up a competitive process based on freely defined criteria. Both can be used with IPD contracts.

Is there a legal barrier for the public sector?

The Code requires selection based on competition and allows for decisions based on a balance of criteria that must include some element of cost - there is an acceptance that the financial criterion can be weighted below 50%. When using the Competitive Dialogue and Innovation Partnership procedures, the Code requires the use of cost rather than price (Art. R.2152-8). The EU 'competitive dialogue' and 'innovation partnership' procedures are two of the EU procurement procedures suitable for use with IPD. A third approach the 'negotiated' procedure has been used to procure public sector construction works in Finland since 2011 (Lahdenperä, 2013). This also demonstrates the feasibility of using the IPD contract approach in compliance with EU Procurement Regulations (EU 2014), which are the basis of the French Code[8].

IPD delivery partners are selected using competitive criteria: e.g. competence, capability and experience as well as price/cost. Can the financial requirement of the code be satisfied by the potential delivery partners' schedules of rates and the amount of profit and corporate overhead that they expect to earn (the **fee** in Figure 2) if the project is completed successfully?

The legal advice received suggests that the available financial information (Schedule of rates and expected fee) is insufficient to enable the client to assess the price or cost criterion within the meaning of Art. R.2152-7 (see above) of the Code. Yet the Code Art. R.2112-6 makes it clear that the inability to determine a final project price is not an obstacle to public procurement, nor is the use of defined unit rates and unknown quantities. In Art. R.2152-9 and -10, the Code gives an example of a cost criterion – lifecycle cost. This includes elements that are unknowable at the time of the contract. The requirements for such a criterion are that it is non-discriminatory, clearly defined and objectively verifiable.

Art. R.2112-6 of the code allows for unit-rate reimbursable contracts. This suggests that the inability to determine a final project price is not an obstacle to public procurement, nor is the use of defined unit rates and unknown quantities.

Despite this, the legal author feels that the use of an IPD contract in the public sector will be difficult to reconcile with the competitive tendering procedures imposed by the Public Procurement Code. That constitutes a barrier to public sector IPD implementation.

Two of the other authors believe that the legal author's interpretation of the law is influenced by her experience of the *normal* way of doing things – the Design-Bid-Build, DBB way. In the DBB way there is an agreed sum for the completion of the project written into the contract.

[8] Although the Finnish use of IPD pre-dates the current version of the EU procurement regulations (EU 2014), the procurement procedure they used (the 'negotiated procedure') was established in earlier versions of the EU procurement regulations and continued in the 2014 version.

It can be argued that when a DBB, contract is signed the final cost is not known. There is an agreed sum for the completion of the project, but almost all construction using DBB costs more than the agreed sum (claims) or delivers a reduced scope. With IPD, clients often spend less than the agreed cost and get greater scope than anticipated. Which of those procurement routes is more *economically advantageous*?

Many government lawyers and many who procure construction for public sector organisations are likely to interpret the code in the same way as the legal author. What this suggests is that the interpretation of the code needs further opinions. Some will doubtless suggest that this needs testing in the courts before they will risk using it. They might have a long wait. An Australian review of AU$43bn worth of projects found zero AU$ spent on dispute resolution (Victoria, 2009)

IPD is a *system change* in construction procurement. As a system change, it requires new thinking habits, new concepts and new language (e.g. *delivery partner* or *trade partner* instead of (sub-)contractor, tier 1-n, etc.). It is difficult, even impossible, to do IPD with a mindset from *normal* construction. These are reasons why it is often difficult for people embedded in *normal* construction to understand what is involved in IPD.

As clearly illustrated in Figure 1, data from IPD-type contracts suggest most contracts complete on or under the target cost and on or ahead of time – the opposite of the outcomes of *normal* contracts (Cheng et al., 2015; Walker, Harley and Mills, 2015). This data also suggests that IPD is more likely to be the *most economically advantageous* procurement route for any public-sector client *provided* they can be sufficiently involved in the management of their projects. Active client engagement in IPD helps to increase the chances of success (Seed, 2022).

CONCLUSIONS

This study aims to identify the legal barriers in adopting Integrated Project Delivery in the French context. First, the challenges that construction sector is facing are highlighted to show the need for an alternative delivery model. Then the main IPD main characteristics are presented. The third part of this paper focuses on the legal – and related – barriers to IPD adoption in both public and private sector.

There are no legal obstacles to the private sector using IPD. The barriers that exist are in the mind and are related to habitual ways of thinking about project delivery.

The review has also demonstrated that the principles on which an IPD contract is based (payment terms, limitation of builder and designer liability, early termination of contract) do not contravene the rules of public policy applicable to private contracts under French law.

The Public Procurement Code requires selection of “the most economically advantageous” offer based on advertised and non-discriminatory criteria that can be qualitative (such as competence, capability and experience) as well as price/cost. In *normal* construction this is often interpreted as the *lowest bidder* even though that is rarely the price finally paid.

IPD uses value-driven selection criteria incompatible with the idea of the lowest bidder. IPD is a system change in construction procurement that requires different thinking and different concepts. It is as if *normal* construction is from Mars and IPD is from Venus.

There is nothing in the Public Procurement Code that requires public sector clients to procure lowest bidders. Over two decades of experience with IPD and similar approaches suggests that *active* clients using a relational contracting approach can provide the *most (economically) advantageous* project outcomes for all stakeholders.

Despite that, our lawyer’s interpretation of the Public Procurement Code is likely to be widely shared in the public sector and beyond. This, if nothing else, will make it difficult for many involved in public sector construction to consider using IPD.

There are barriers to IPD adoption by organisations in the public sector — it seems clear that they are unlikely to be legal – they may be based on old (*normal*) thinking habits and assumptions.

OPPORTUNITIES FOR FURTHER RESEARCH

It will be useful to have:

- Further opinions from other lawyers
- Opinions about alternative relational contracts
- A discussion of relational contract theory in the context of the French legal system may help in this discussion. French and Anglo-Saxon legal systems are different.
- A discussion of cultural and behavioural barriers to IPD in the French context.

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STRATEGIC PARTNERSHIPS – BEST PRACTICE ACROSS NORWAY AND DENMARK

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ABSTRACT

In recent years, the concept of strategic partnerships has gained attention in the Norwegian and Danish construction industry. As a project delivery method, strategic partnerships share similarities with the Lean project delivery perspective and Integrated Project Delivery (IPD) as they all seek to achieve more collaborative projects. In this paper we will compare strategic partnerships, strategic partnering and IPD based on literature reviews and experiences from recent strategic partnerships and strategic partnering in Norway and Denmark. The paper explains strategic partnerships and partnering by structuring it according to three essential Lean Construction (LC) elements: Commercial, organizational, and operating system.

A combination of literature review and document study was used for data collection. Also, online meetings with all authors participating were completed to discuss and analyse data.

Experiences from a Norwegian case study and Denmark points to several success criteria that are crucial for the success of long-term collaboration, such as multi-project framework agreement, keeping the same people, and support from the management. Some of the success criteria stem from IPD and others might also be a positive application for IPD.

KEYWORDS

Strategic partnerships, Strategic partnering, IPD, lean construction, collaboration.

INTRODUCTION

Bennett and Jayes (1995) defined partnering as a management methodology used to achieve increased value and productivity in the construction industry. The concept of partnering focuses on improving cooperation between the parties involved (Lahdenperä, 2012). This paper divides partnering into three categories: Project partnering, strategic partnering and strategic partnerships. The former is a collaboration between a client and a delivery team (Architects, designers and main contractor) that are specific to a particular project (Lahdenperä, 2012). With strategic partnering, a delivery team collaborate on more than one project, but a separate contract for each specific project (Paulsen et al., 2022). However, with a strategic partnership, a client offers a portfolio of upcoming projects over several years in a single package to a delivery team (Værdibyg and Rebus 2021a). Research from Denmark and Norway shows great potential when implementing strategic partnering and strategic partnerships in the construction industry (Gottlieb et al. 2020; Paulsen et al. 2022; Værdibyg and Rebus 2021a; b). In Denmark,

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they have moved from project partnering to a focus on strategic partnerships with long-term contracts whereas in Norway the recent focus has been on strategic partnering. Thus, the Danish approach goes more in the direction of a programme perspective where a group of related projects are aligned and coordinated to achieve benefits that are not possible when projects are managed individually (Shehu and Akintoye 2009).

This paper has structured strategic partnership into three elements: Commercial, organizational, and operating system, based on the LC triangle described by Ballard (2012). All three elements in the LC triangle are crucial to achieving a successful strategic partnership. Partnering as a project delivery method shares similarities with the Lean perspective as they both use contractual-, organisational-, and cultural elements to achieve a collaborative project (Falch et al., 2020). Since strategic partnering is an extension of traditional partnering, the similarities with the Lean perspective are even higher for strategic partnering (Paulsen et al. 2022). The reason is that, over a more extended period, companies can eliminate problems and ensure ongoing improvement through a more open and frequent exchange of information (Shimizu and Cardoso, 2002). Thus, strategic partnerships and strategic partnering can reduce waste and increase value in construction projects. Also, strategic partnering shares similarities with IPD as they accommodate the construction industry´s need for more efficient collaboration between project participants (Lahdenperä, 2012).

This study aims to identify improvements in current strategic partnering and strategic partnerships. The target group for this study is researchers and construction practitioners who want to develop strategic partnerships. Previous research shows positive effects from strategic partnering in Norway (Paulsen et al. 2022), strategic partnerships in Denmark, (Værdibyg and Rebus 2021a; b) and IPD (AIA 2007; Fischer et al. 2017). However, no one has yet compared the similarities, the differences, or whether the different approaches can learn something from each other. Therefore, this paper seeks to answer the following research questions:

1. What can be learned from the different approaches to strategic partnerships in Norway and Denmark?
2. What is needed to achieve a successful strategic partnership?

METHODOLOGY

This paper reports our exploratory approach towards creating a more coherent view of the concept of strategic partnerships from a lean construction perspective and in the context of the Norwegian and Danish AEC industry. The research idea stemmed from a case study by Paulsen et al. (2022) presented at IGLC 2022, which to the authors' knowledge is the only case study of strategic partnering from Norway. The case study included four school building projects where the same contractor and design company had partnered up four times from 2014 to 2022. Fifteen interviews were conducted and supplemented by a document study of the respective tendering documents, the contracts and meeting minutes from the four projects. The interviews were semi-structured, meaning that they followed a standardized interview guide (Blumberg et al. 2014). The informants all had key roles in the projects. For example, the project manager, design manager and Processing supervisor were interviewed. These people were involved in all four projects. The study design followed the prescriptions of Yin's (2014) case study approach.

To anchor the empirical insight and to ensure relevance to lean construction, a literature review was conducted. The initial review was carried out primo 2022 by searching in the databases Scopus, Google Scholar and Oria. The latter is the Norwegian universities' library database. The literature survey was supplemented with new searches ultimo 2022, to clarify improvements to strategic partnering. The existing documentation from studies on strategic partnering is scarce, especially in the context of lean construction theory and IPD. However, qualitative methods are well-suited for explorative purposes (Thagaard, 2018). Consequently, it was decided to carry out a continuation of the initial research work based on feedback gained at IGLC 2022. Particularly, contact was made with the Danish NGO "Værdibyg" (The Value Creating Construction Process). Strategic Partnership has gained a foothold in Denmark. Empirical experiences are well documented in guidelines and research reports. A natural continuation of our work on the theme was therefore to compare Norwegian and Danish experiences and then draw the lines to the principles of IPD and Lean philosophy.

To corroborate the findings from the Norwegian case study documented by Paulsen et al. (2022) it was decided to carry out an in-depth document study as data collection methodology. Through Værdibyg the following documents for the in-depth document study were identified:

- Strategic Partnerships - From Idea to Contract.
- Strategic Partnerships - Implementation of the Collaboration.
- Long-term strategic collaboration in the construction industry.
- Strategic Partnerships in the Municipality of Copenhagen.
- Experiences and Facts about Strategic Partnerships.

The documents were analyzed using a qualitative approach where the findings from the selected documents were categorized according to the LC Triangle. According to Bowen (2009), this form of document analysis could be defined as a systematic procedure for reviewing or evaluating documents to create or obtain empirical data. The use of the predetermined categories given by the LC triangle made the analysis an iterative process.

In sum, we report from an exploratory comparison between how strategic partnering/partnership is practised and perceived in Norway and Denmark through the lens of lean construction theory. The study is limited to a single Norwegian case whose empirical findings are compared to the Danish practice described in selected guidelines and research reports. Although the study is limited to this geographical location, we believe that there are general learning points here that are interesting for Lean Practitioners.

THEORETICAL FRAMEWORK

A core principle for Lean project delivery is described using the LC triangle, which describes the three fundamental elements in all project delivery methods: Commercial, organizational and operating system (Ballard, 2012; Howell, 2011; Thomsen et al., 2010). Lean project delivery seeks to align all project parties to achieve a collaborative project organization with available contractual elements and create a project culture for delivering value (Falch et al., 2020).

Construction projects can be delivered through various delivery methods, ranging from traditional design–bid–build (DBB) to more integrated forms such as partnering, Lean Project Delivery System (LPDS) and IPD. The project delivery method dictates how the project team engages, how different parties get involved, and the means used (Engebø et al., 2021). Other examples of project delivery methods for single collaborative processes are Partnering, Integrated Project Delivery, Alliancing, Relational contracting, and Relationship-based procurement (e.g., Engebø et al. 2020). These methods have both similarities and differences. Nyström (2005) applied Ludwig Wittgenstein's idea of family resemblance to conclude that trust and mutual understanding are necessary components in every partnering project (similarities), while there are components that vary from project to project (differences). However, this paper focuses on so-called collaborative project delivery methods across several projects that seek to integrate and align the parties early, i.e., already in the planning phase.

LPDS AND IPD

The LPDS is a delivery system in which the project team helps clients and customers (beneficiaries) to decide what they want (Ballard 2000; Khanzode et al. 2005). Ballard (2000) describes LPDS as a "project-based production system" because it is a temporary production system. LPDS contains five project phases: Project definition, lean design, lean supply, lean assembly, and use. Each phase also contains three project steps. The phases are interconnected to the next one through a common project step. Therefore, each project phase is influenced by the previous phase and has an impact on the following phase (Ballard 2000). In contrast to traditional project delivery systems, LPDS questions at the very beginning of the project what needs to be done and who is responsible for the task. Compared to traditional project delivery like DBB, LPDS explicitly shows the relations and dependencies between the different phases through a construction project, which are often ignored (Ballard 2000; Nguyen et al. 2008).

IPD (as described by i.e., Fischer et al. (2017)) is a project delivery method that integrates people, systems, organizations, and practices into a single collaborative process. The aim is to optimize results and value to the owner, reduce waste and maximize efficiency through all phases of the project (AIA 2007; Dargham et al. 2019). Lahdenperä (2012) describes that an IPD contract is a multi-party contract between several actors, and for example not only between the client and the contractor. Multiparty contracts are not common within what has traditionally been called partnering (Lahdenperä, 2012). Contractually, IPD differs from strategic partnership. Collaboration with the client and application of Lean tools is also common in IPD projects (Fischer et al., 2017). Research on the IPD shows benefits linked to risk sharing, improved productivity, and increased quality of work (AIA, 2007).

STRATEGIC PARTNERSHIPS/ PARTNERING IN A LEAN PERSPECTIVE

Partnering as a project delivery method shares similarities with the Lean perspective as they both use contractual-, organisational-, and cultural elements to achieve a collaborative project (Falch et al., 2020). Since strategic partnering and strategic partnerships in several ways are an extension of project partnering, the similarities with the Lean perspective are even higher (Paulsen et al. 2022). The reason is that companies in the long run can eliminate many of their problems and ensure ongoing improvement through a more open, frequent, and accurate exchange of information (Shimizu and Cardoso, 2002). Thus, strategic partnering as a project delivery method can both reduce waste and increase value in construction projects. Even if the Lean Construction concepts are more related to firms, they can be extended to the organization level (Shimizu and Cardoso, 2002), as in this paper.

Sundquist et al. (2018)'s study points out research gaps regarding the actual features of strategic partnering. From a Lean perspective, IPD has, in recent years, been given more attention than strategic partnering (see for example, Dargham et al. 2019; Simonsen et al. 2019). Part of the explanation probably lies in the fact that IPD projects are more linked to the use of LC tools and BIM, compared to partnering (Lahdenperä 2012). However, IPD shares similarities with strategic partnering as they accommodate the construction industry´s need for more efficient collaboration between project participants (Lahdenperä, 2012). Therefore, this paper is placing strategic partnering in a setting of IPD`s basic structure. Howell (1999) has said that "Partnering can be a solution to the failure of central control to manage production in conditions of high uncertainty and complexity". If this is true, strategic partnering can be a way to get Lean issues effectively into companies.

FINDINGS

This section presents results related to the research questions and the LC triangle.

STRATEGIC PARTNERING IN THE NORWEGIAN CASE STUDY

Commercial

In this particular case, the contractor entered a contract with the client, and the contractor had contracts with a design company and an architect company. The delivery team implemented strategic partnering as an informal agreement and separate contracts were signed for each project. The client is not included in the partnering collaboration. Because of the informal agreement and separate contracts, the Norwegian case study showed that such long-term collaborations entail a degree of uncertainty. First, it is difficult to predict which future projects will be put out to tender, and second, there will always be uncertainty about whether the tendering competition will be won. Also, it was found that several partnering elements were stipulated in the contracts to improve the collaboration from project to project. The most important were start-up seminars, team-building activities, open book, and joint meetings with the client and users. However, no contractual incentives were used between the parties (Paulsen et al., 2022). A fixed-price contract is most common, which means that the client relinquished the risk related to the cost of the projects to the delivery team.

Organizational

Full delivery team (architects, designers, and main contractor) are included. The parties use a collaborative project delivery method with early contractor involvement, project hotels and BIM as digital collaboration tools. The interviews showed that keeping the same key personnel was a strategic aim from the beginning of the strategic partnership. For example, the project manager and the design manager were the same person in all four projects (Paulsen et al., 2022).

The delivery team focused on becoming more productive, and results from the case study showed that they managed to increase productivity and recurring effects from project to project. However, the recurring effects were not as significant as hoped because keeping the same people from project to project is challenging. External factors such as the client were one of the reasons why it was challenging to keep the same people through the strategic partnership, among other things due to political decisions which led to postponements. Also, the client's indecision negatively affects the strategic partnership. Therefore, an insight from the Norwegian case study, showed that external factors such as the client could significantly influence the relationship between the parties in the delivery team (Paulsen et al., 2022).

Operating system

There were three main reasons why the delivery team implemented strategic partnering: 1) They had some prior positive partnering experiences from other projects, 2) together, they believed they could form a competitive team that would stand a better chance at winning tendering competitions, and 3) the desire to achieve a repetition effect. The informants from the case study describe that the relations at the individual level developed well and that people have built close ties across the companies. The professional collaboration also led to improved productivity and increased quality of the work. Another positive effect documented was the delivery team`s strong performance in the tender competitions. Their strategic partnering collaboration was crucial to the team winning four school projects in a row, the informants said. However, the case study showed that sustained strategic partnering over time creates tension between the organizations, due to economic conflicts (Paulsen et al., 2022).

The case study showed that the delivery team agreed that they should have been better at continuously evaluating the collaboration during the strategic partnership. They also acknowledge that they failed to eliminate problems. As a result, the same problems recur in all four projects. Another characteristic worth noting was that no formal organizational agreement was drawn, making the intention and commitment purely relational (Paulsen et al., 2022).

Strategic Partnerships in Denmark

The first strategic partnerships in Denmark were established in 2016. The earliest strategic partnerships were inspired by cases from UK and Sweden (Kadefors et al., 2013), and alliancing in Finland (Lahdenperä, 2012). There are currently nine active strategic partnerships with a combined expected value of approximately three billion euro (Frederiksen and Johansen, 2022).

Commercial

In the Danish construction sector, a strategic partnership is defined as a long-term collaboration between a client and a delivery team on a collective project portfolio (Værdibyg and Rebus, 2021a). The clients from the nine active strategic partnerships are four municipalities, three social housing companies, one region and one governmental. the type of projects are schools, daycare centers and social housing. All the nine active delivery teams include at least one contractor as well as an architect and the designers. The partnership agreement between the client and the delivery team is typically based on a framework agreement, where the contractor is fronting a consortium. That means that new contracts can be assigned to the partnership without separate tenders on an ongoing basis over the contract period. The long-term aim of the collaboration is to provide the opportunity for the client and the delivery team to build an organization across the companies involved and to work with the development, innovation and optimization of solutions and processes.

For previous strategic partnerships, the contract period has been four years, but projects initiated within the four years can be carried out and completed subsequently so that the partnerships' tasks extend beyond four years. In most of the Danish strategic partnerships, there has been no guarantee of a minimum volume of tasks and in their set-up, they have chosen that both the client and the delivery team can stop the collaboration at any time. None of the nine partnerships has used this opportunity yet. The tender documentation has often contained a risk model that defines the distribution of risk between the parties. For delivery teams, it has been a challenge to create a common business model and to share responsibilities and risks in a collective setup. Many of the Danish partnerships have a risk pool for unforeseen expenses and improvements. A partnership is about having an interest and insight into each other's basis for decision-making and risk elements, and thus it is appropriate that people do not try to place responsibility on one party alone. Often in the partnerships, everyone is willing to jointly manage the risks of the projects and discuss how to handle matters when faced with an incident or uncertainty. It can be risks regarding quantities, design errors or execution risks, where the parties can agree on how to best solve it overall (Værdibyg and Rebus, 2021a; b).

Organizational

The tender process has primarily been based on qualitative evaluation criteria. Often, the client has conducted a market dialogue in advance to ensure that there is a market for a partnership. This has also been an early warning to the companies, who then began teaming up with collaborators they would submit a bid with. The tender documentation often contains a description of the client's organisation, decision-making processes, and business processes. The partnerships have in most cases used the standard documents and agreements of the Danish construction industry as a basis for the projects. The experiences show that it is important that each company are willing to enter a value-based collaboration. All parties must have strong managerial support for entering a strategic collaboration.

In strategic partnerships, the delivery team has close collaboration with the client. In the contractual agreements, there are defined common goals and values as well as the team uses "open books" for pricing the construction costs of the projects. Furthermore, the experience is, that keeping the same personnel for several projects produces positive effects, such as repetition effect and better cooperation (Frederiksen and Johansen, 2022; Værdibyg and Rebus, 2021b). Also, many of the strategic partnerships become so close, that they begin to work as a uniform company with people being employed (and laid off) directly to the strategic partnership.

Operating System

Once the strategic partnership has been formalized between the client and the delivery team, there has been a great deal of work in establishing the collaboration and getting the many organizations involved into a position to act as a single partnership. Most of the strategic partnerships have a joint project office to support the common culture. To ensure the necessary managerial attention and decision-making power in the strategic partnership, a joint organization has been established in all strategic partnerships between the client and the delivery team. Often as a three-part management structure: 1) steering committee, 2) operational management, and 3) project management. The steering committee handles the strategic management of the partnership and can be compared to the board in a large corporation. The operational management handles the day-to-day management of the partnership and can be compared to an executive board. The strategic partnerships consist of key persons from 3-5 of the central actors in the partnership. The specific work of developing and implementing the individual projects in the portfolio takes place at the project management level.

The project portfolio is planned to suit both the client and the delivery team. The client has the primary responsibility for the management of the project pipeline, while the responsibility for the management of the ongoing project portfolio lies jointly with the operational management. The projects that are chosen to be completed in the partnership are implemented in several phases that often are divided into the following steps: 0) Clarification of needs, 1) planning, 2) project proposals and pricing, and 3) design, execution and handover. The long-term collaboration and repetition in projects and processes have given greater budgetary security, fewer conflicts, no expenses for lawyers, better delivery on time, and better quality for both the client and the delivery team. With many projects in the portfolio, there has been an improvement in processes and cooperation and the parties have gained a closer relationship and a deeper understanding of each other. This is, among other aspects, caused by keeping the same personnel for several projects with ongoing relations and collaboration between persons from different companies (Gottlieb et al., 2020). In the next phase of strategic partnerships in Denmark, there has been a much larger focus on sustainability and the delivery team's ability to prove the construction project to be cheaper than "traditional" projects.

Figure 1 summarizes the similarities and differences between IPD, Norwegian strategic partnering and Danish strategic partnerships in a Wittgenstein family-resemblance sunflower model. The figure is inspired by Nyström (2005).

Figure 1: IPD (blue), Norwegian strategic partnering (green) and Danish strategic partnerships (red) in a Wittgenstein family-resemblance sunflower model (inspired by Nyström, 2005).

DISCUSSION

In this section, the authors will discuss similarities, differences, or whether the different approaches can learn something from each other. The discussion is based on the findings presented in the results section. Table 1 shows a summary of the key findings of this study.

Table 1: Key findings. Strategic partnering and strategic partnerships in a setting of IPD.

Elements	Norway	Denmark	IPD
Commercial:			
Design-build	x	x	
Multi-party contract			x
Framework agreement		x	
Ability to win projects	x		
Risk Sharing		x	x
Organizational:			
Full delivery team	x	x	x
Same people for several projects	x	x	
Repetition effect over projects	x	x	
Support from the management		x	x
Operating system:			
Improved productivity	x	x	x
Increased quality of the work	x	x	x
Collaboration with the client		x	x
Application of Lean tools			x

DIFFERENT APPROACHES TO STRATEGIC PARTNERSHIPS

Commercial

Both in Norway and Denmark, the client entered a design-build contract with the contractor, while the contractor had contracts with designers and architects. Since the client was not part of the strategic partnership, a multi-party contract was not entered into as in IPD projects. In Denmark, the legal basis for the partnership agreement between the client and the delivery team is typically based on a framework agreement. With the Danish approach, the delivery team doesn't need to worry about which future projects. However, with the Norwegian approach, the delivery team depends on the local business environment, local economy, and government regulations to get new projects. In the public domain, it seems like the biggest barriers to strategic partnering lie in the lack of opportunity to manage projects at a portfolio level. This is mainly because public clients are given a mandate and funding for individual projects. The second barrier is the law on public procurement, which sets requirements for the contracting process. Thus, most strategic partnering will take place in the value chain under the client. The Danish model facilitates continuous evaluation of the collaboration during the strategic partnership. With the Norwegian approach, it is uncertain whether the parties will collaborate on future projects. Nevertheless, the results show that strategic partnering in Norway gives a competitive advantage when it comes to winning projects, while it is still unclear whether strategic partnerships in Denmark do the same. In some of the strategic partnerships In Denmark, there are internal agreements of shared risk between the companies in the partnership. This allows the delivery team to focus their energy on quick solutions rather than on placing risk, blame and responsibility for errors. This approach is also highlighted as part of the simple framework of IPD projects (Fischer et al., 2014).

Organizational

In all collaborative project delivery methods included in this paper, there is a predetermined delivery team who tries to win projects together. An advantage of strategic partnership and strategic partnering, which IPD does not necessarily have, is that the delivery team can use the same people in several projects. Both results from Norway and Denmark show that keeping the same personnel for several projects produces positive effects, such as the repetition effect. However, In the Norwegian case projects, the repetition effects were not as significant as hoped because keeping the same people from project to project is challenging. External factors such as the client were one of the reasons why it was challenging to keep the same people. The chance of this happening is perhaps less with strategic partnerships in Denmark, since the client has a larger share of the risk, compared with the Norwegian approach. Also, Fischer (2017) has pointed out that keeping the same people is a challenge for IPD projects, but on a project level.

As the strategic partnerships in Denmark are rather large contracts all the companies in the partnership have a special focus on the work they do within the partnership. Therefore, there is also a willingness from top management to get the partnership to work as an efficient entity as this is the best way to get profits and to get more work within the framework agreement. However, in the Norwegian case projects, it was identified lack of support from the management. The consequence was that the delivery team did not continuously evaluate the collaboration during the strategic partnership and the same problems recur in all projects.

Operating system

Results from Norway and Denmark show that the relational collaboration between the people within the delivery team has positive effects on the professional collaboration. Research and experiences suggest that strategic partnerships and strategic partnering lead to improved productivity and increased quality of work. From the Norwegian case study, the informants describe that there has been a good development of relationships at the individual level across the companies. However, at the company level, the Norwegian case study showed that a negative relationship was developed due to financial and contractual conditions. In Denmark, on the other hand, such problems have been avoided because the strategic partnerships have a joint project office to support the common culture. Also, to ensure the necessary managerial attention and decision-making power, it is common to establish a joint organization. With IPD, such problems are also less likely because it is a multi-party contract which means that all parties are more dependent on each other to achieve the project goals. Therefore, the overall assessment shows that the Danish approach and IPD makes the parties work more towards the same goals, while the parties in Norway are more concerned with their profits.

Success Criteria for Strategic Partnerships

Our comparisons across both existing research and the experiences from Norway and Denmark point to several key activities or criteria that are crucial for the success of long-term collaboration in either strategic partnering or strategic partnerships. Some of these stems from IPD and others might also be a positive application for IPD projects.

Opportunity to win more contracts

The setup of a strategic partnership or an ongoing strategic partnering across several projects helps optimise the internal processes and this will make the partnership able to give better bids to other construction jobs with other clients offering an experienced and united team with optimised delivery processes. This will most often result in both better quality and lower prices (or more accurate prices) in new tenders.

Long-term, multi-project framework agreement

A portfolio of projects as opposed to single project contracts gives the possibility and project volume to invest in the shared organizational setup as well as benefitting from both the repetition of processes and the long-term relations across the participating companies and employees. This also provides the foundation for a shared learning organization with a solid basis for the application of Lean tools across different projects. The learning and application of

Lean tools result in better project delivery and productivity. Based on our research we cannot say how long the contracts should be. Four years may be a suitable length with the opportunity to renew the contract if all parties are interested in continuing.

Keeping the same people across projects

The multi-project contracts of strategic partnerships allow keeping the same people from different companies together for several projects, something which both enriches the projects as well as employee satisfaction and long-time employment.

Risk sharing

By sharing risk between the companies, the focus is on solving problems rather than placing or avoiding blame. This keeps participants aligned in the shared goals of delivering good projects.

Support from the management

Larger contracts seem to attract more attention from top management which also gives the benefit of easier access to company support in case of problems within the strategic partnership.

Collaboration with the client

For multi-project contracts it is possible to have a closer collaboration with the client to solve the projects in unison as they come. This also calls for an engaged and active client that can be part of the partnership and assign managerial resources permanently to the partnership projects to make good and quick decisions that keep the projects running and on target.

CONCLUSIONS

In this paper, a study was conducted to research different approaches to strategic partnerships. A comparison between IPD and Lean construction was also made to examine the differences. Therefore, this paper has placed strategic partnerships in a setting of Lean philosophy to see if strategic partnership can be a solution to the failure of central control to manage production in conditions of high uncertainty and complexity. As the study only emphasized strategic partnerships in Norway and Denmark, the results should not be viewed as a generalization of the phenomena. Instead, this study may provide deeper insight into the phenomena and be of value to those considering strategic partnership. In addition, this paper can contribute to the theory of strategic partnership, especially from a lean perspective.

Figure 1 summarized the differences between IPD, Norwegian strategic partnering and Danish strategic partnerships. The Danish approach facilitates continuous evaluation of collaboration during the strategic partnership to a larger extent than in Norwegian strategic partnering projects. The risk sharing between companies and support from the management in the strategic partnerships in Denmark gives advantages to the delivery team related to finding quick solution rather than on placing risks and continuously evaluating the collaboration. Also, if the client is more involved in the collaboration, results from Denmark and IPD shows that the parties work more towards the same goals, compared with Norwegian strategic partnering.

Experiences from Norway and Denmark point to several success criteria that are crucial for the success of long-term collaboration, such as multi-project framework agreement, keeping the same people, and support from the management. Some of the success criteria stem from IPD and others might also be a positive application for IPD projects, like the opportunity to win more contracts and get people to collaborate on multiple projects.

There is still a lack of proof of how well strategic partnership is working in practice. For example, more quantitative research is needed to measure quantifiable performance data such as productivity and quality. Therefore, more case studies and interdisciplinary research are needed to further clarify improvements.

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INTEGRATED PROJECT DELIVERY (IPD) FOR HEALTHCARE PROJECTS: A COMPANY-SPECIFIC ANALYSIS

A.S. Hanna[1], Z. Zhu[2], and J.T. Morrison[3]

ABSTRACT

Organizations are increasingly looking to Integrated Project Delivery (IPD) to provide leaner and more successful projects in their construction efforts. Of particular interest is IPD in the healthcare sector, which has a higher instance of megaprojects and a higher overall level of complexity and risk. Therefore, the risk-sharing model espoused by IPD is more attractive than conventional delivery like Design-Bid-Build (DBB) or Construction Manager At-Risk (CMR).

A major contractor worked with the researchers to evaluate its performance on two recent healthcare projects on which it deployed IPD techniques as the first step in a potential organizational shift to the IPD paradigm. Eleven projects were collected – the two IPD projects as well as nine similar projects delivered under CMR within the last five years. These were compared to twenty healthcare projects completed by other firms in terms of eighteen key performance metrics.

Logically, lean ideals native to IPD led to better performance in several metrics; particularly those that have been previously identified as strongly correlated with project success such as cost and schedule growth, as well as in overall project performance in terms of the Project Performance Index (PPI). Buoyed by strong results, the company intends to continue with IPD.

KEYWORDS

Integrated project delivery (IPD), lean construction, process, project delivery systems, project performance

INTRODUCTION

It is an indisputable fact that healthcare construction in the United States will continue to experience increases in demand over the next several decades. For proof of this sustained increase, one needs to look no further than a U.S. Census Bureau forecast. Vespa et al. found that in the year 2020, it was estimated that 56.1 million individuals (or roughly 17% of the population) were over the age of 65, but by 2060, these numbers are due to increase to 94.7 million and 23%, respectively (2020). Therefore, it is unsurprising that inpatient care days in hospitals and medical facilities are forecast to outpace population growth by 22% by 2050 (Pallin et al, 2014). It is thus logical that U.S. construction spending in the healthcare sector

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increased from $42 million per month in January 2013 to $55.7 million in January 2023, an increase of 32% in a decade (Federal Reserve Bank of St. Louis, 2023).

Accordingly, there are an increased number of firms seeking to enter the healthcare construction space and/or improve their existing practice in that area. It was forecast that construction firms that work in the healthcare space should continue to enjoy "growth in revenue, profit, and backlog," given that supply-chain issues and inflationary pressures have not slowed the rate of healthcare construction executed or planned, characteristic of the sector's historical steadiness even through economic uncertainty (Obando, 2022).

One such firm, a top-twenty contractor in the United States as reported by the Engineering News-Record (ENR), has a large and successful healthcare construction practice but had only just begun to implement integrated project delivery (IPD) on healthcare-sector projects[4]. This is in line with previous research: an American Institute of Architects (AIA) survey in 2011 found that a much higher percentage of its members reported "awareness" (83%) or demonstrated an "understanding" of the IPD system (40%) than had ever executed a project under that model (13%) (AIA Center for Integrated Practice, 2012).

The low industry penetration of IPD is due to various entrenched obstacles. As was found by Fish, the three principal obstacles to IPD adoption are unfamiliarity with or unavailability of suitable contract documents for the requisite multiparty agreements, lack of available insurance products in the marketplace that are appropriate for the risk-sharing paradigm, and difficulty aligning the project team to the necessary culture of facilitation (Fish, 2011). Building upon this work, Kahavandi et al. identified that contractual challenges were the most significant, followed by environmental factors (including legislative obstacles and insurance product availability) (2019).

Beyond these enumerated obstacles, there is another perception-related barrier to IPD use. While volumes have been written extolling the virtues of lean construction by academia, and IPD, some research has argued that IPD has almost become overexposed and that the industry-wide publicity of IPD leads to inflated expectations, becoming in fact a further obstacle to adoption (Bilbo et al, 2014).

Given that major contracting firms of the type which engaged the researchers for this investigation are exceptionally risk-averse and can be opposed to sharing information to the degree that IPD requires, leaders of change who were internal proponents of IPD needed to present a quantitative-based analysis of the pilot projects' performance to help make their case and overcome the obstacles previously noted (Zachariah & Goldsmith, 2022). Thus, the researchers were engaged by the company to perform such an analysis.

OBJECTIVES AND SCOPE

In order to assist the company in its analysis of its IPD pilot efforts, the following research objectives were set forth: 1) understand what performance metrics had the most impact on the key stakeholders in the company; 2) quantify those performance metrics for the IPD pilot projects as well as other comparable projects within the company's portfolio delivered by other methods; 3) compare the company's performance under both IPD and non-IPD delivery models to the industry at large; 4) present results in a clear and engaging way; and 5) create a process that could be repeatable at other companies, thus generating a benefit to the healthcare construction sector at large as it seeks to become leaner and incorporate IPD more significantly.

Throughout this paper, IPD is used not only to represent the delivery system but also as a shorthand for the lean techniques and practices that are inherent to it. This is because it is difficult to realize the desired benefits of IPD without embracing and implementing lean practices. The Construction Industry Institute (CII)'s research team DCC-06, led by Hanna,

[4] To protect confidentiality, the firm in question will not be named, but will be referred to as 'the company' throughout.

noted that the use of lean techniques was a key concept imperative to an IPD deployment (Hanna & Morrison, 2021).

RESEARCH METHOD

The study presented herein was conducted in four principal phases, as presented in Figure 1. Each phase is characterized in detail in the following sections.

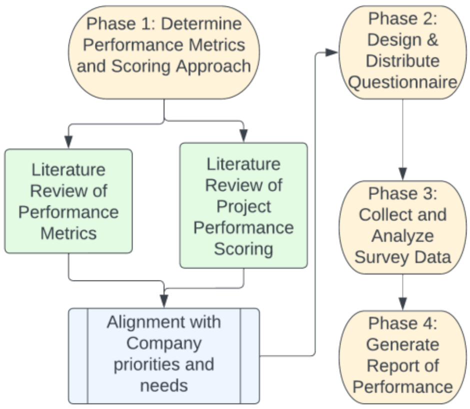

Figure 1: Research Method Overview

LITERATURE REVIEW AND METRIC/SCORING SELECTION

PROJECT PERFORMANCE METRIC SELECTION

There is a significant body of work in project performance analysis which contains a variety of different scoring systems and performance metrics to compare projects. The general chronology of project delivery systems both over time (in terms of adoption) and effectiveness (in terms of project performance) proceeds from Design-Bid-Build (DBB) to CMR, then to Design-Build (DB)[5] and culminates with IPD (Ibrahim & Hanna, 2019).

To determine what performance metrics to utilize in their analysis, the researchers worked closely with representatives from the company to assess what metrics informed their operating decisions. Particularly useful in this discussion was the work of Iskandar et al., who performed a healthcare-focused quantitative analysis of project performance. Among the most significant metrics identified by the Iskandar study were: design quality (as measured by requests for information (RFI) per million dollars), construction speed, schedule growth and cost growth (Iskandar et al. 2019). However, Iskandar did not compare projects through the lens of project delivery systems.

Similarly, Labib performed a two-part model development on a dataset composed of state-financed projects, which included a high percentage of institutional work. Labib's model formulation was based on eight metrics, and had among the most robust validation process in the literature (Labib, 2019).

Per the method agreed upon by the researchers with the company, the company reviewed the performance metrics to assess which could reasonably be tracked by their project staff, and which were of import to their decision-making. The resultant eighteen metrics, divided into eight holistic areas, that were selected from the literature and augmented by the company's business intelligence needs are presented in Table 1, below, alongside definitions thereof which serve to ensure an understanding of the metrics in use by the reader and to improve the portability of the approach to other companies who might wish to perform a similar analysis.

[5] DB is occasionally interchangeably referred to as Engineer-Procure-Construct (EPC).

Table 1: Selected Performance Metrics

Area	Metric and Type		Definition/Formula
Communication	RFI per $1M	Ratio	$\frac{\text{Number of Project RFI}}{\text{Project Cost in Millions}}$
	RFI processing time	Number	Count of days between submission of an RFI and a resolution
Change Management	Change order processing time	Number	Count of days between submission of a change order and a resolution
	Absolute Value of % Change	Ratio	$\frac{\text{Absolute Change Amount}}{\text{Project Total Cost}}$
	Specific Factor-Related % Change[6]	Ratio	$\frac{\text{Change Amount due to Factor}}{\text{Project Total Cost}}$
Business	Company Image	Scale	5-point Likert scale[7]
Quality	Project System Quality	Scale	5-point Likert scale
	Punchlist items per $1M	Ratio	$\frac{\text{Count of Punchlist Items}}{\text{Project Total Cost}}$
Safety	OSHA Recordable Rate[8]	Ratio	$\frac{(\text{OSHA Recordable Injuries}) * (200{,}000)}{\text{Total Project Work Hours}}$
Cost	Construction Cost Growth	%	$\left(\frac{\text{Actual cost} - \text{Initial estimated cost}}{\text{Initial estimated cost}}\right) * 100$
	Budget Factor	Ratio	$\frac{\text{Actual cost}}{\text{Initial estimated cost+Cost of approved changes}}$
Schedule	Construction Speed (ft^2/Day)	Ratio	$\frac{\text{Construction ft}^2}{\text{Construction Duration (Days)}}$
	Schedule growth	%	$\left(\frac{\text{Actual duration}-\text{Target duration}}{\text{Target duration}}\right) * 100$
	Schedule intensity ($/Day)	Ratio	$\frac{\text{Final Construction Cost}}{\text{Construction Duration}}$
Labour Productivity	Work Value per Labour Cost	Ratio	$\frac{\text{Sell Value of Self} - \text{Performed Work}}{\text{Self} - \text{Performed Labour Cost}}$

PROJECT PERFORMANCE SCORING METHOD

In selecting a scoring tool to use here, one must consider that IPD is a more recent iteration in construction, which disqualifies from consideration the notable preceding work of Konchar and Sanvido (1998), Ibbs (2003), Rojas & Kell (2008), and Sullivan et al. (2017) among others which did not consider IPD. Additionally, while these studies and the general body of literature of which they are representative have done a great deal to advance the operational understanding of PDS in the industry, there is another factor by which this effort was constrained: many previously published works include a great deal of analysis and/or quantification of performance metrics, but lack a unifying method or standardization approach

[6] Three versions of this metric were assessed: Program-related, Design-related, and Quality-related percent change, bringing the total to 18.

[7] All 'scale' metrics were of interest to the company but are not used for quantitative analysis due to their qualitative nature.

[8] While safety is of paramount importance to the construction industry at large and to the company in question, previous research has found that safety is largely ingrained in company culture to the point where it is independent of PDS (Hanna & Morrison, 2021). As such, safety factors were gathered but are not assessed or reported.

by which a project's performance can be distilled into a single number. This is an attractive proposition for industry professionals, as it more easily facilitates the comparison of projects to each other and makes for simpler reporting to leadership. Standardization also facilitates a more ready comparison of projects in a like-to-like fashion.

Therefore, the preceding work the authors could consider for application in this effort consists of work published largely since 2016 which considered IPD. The work fitting this description which was considered included El Asmar et al. (2016), Ibrahim et al. (2018) and the combination of Labib (2019) and Hanna & Morrison (2021).

Among El Asmar et al.'s most notable research contributions were their observation that there was a significant gap in the literature - a single, comprehensive metric to assess project performance did not yet exist - and their creation of the Project Quarterback Rating (PQR) to begin addressing it (2016). The PQR was comprised of 23 individual metrics within seven holistic performance areas, namely: customer relations, safety, schedule, cost, quality, financial performance, and communication (El Asmar et al. 2016). However, while IPD was included by the El Asmar study, only 35 projects in total were considered, and IPD was at the time "emerging" by the study's own admission (El Asmar et al. 2016). Furthermore, the El Asmar study was based in part upon subjective weights (i.e. opinion based) which reduce its accuracy as compared to more recent efforts.

Ibrahim et al. reported in the Construction Research Congress a robust investigation of 12 performance metrics in six areas, considering IPD alongside DBB, DB, and CMR, but the focus of the study was not on a distillation of this analysis into the kind of single numeric score the researchers and the company were seeking (Ibrahim et al. 2018).

The researchers had previously reviewed with the company the Project Performance Index (PPI) which was developed by Labib. However, the original work of Labib was based on a dataset that, while it contained numerous institutional projects that are comparable to healthcare-sector work, did not contain IPD projects (Labib, 2019). Enter the work of Hanna & Morrison, which validated the applicability of Labib's model on IPD projects in the course of their own development of the Project Performance Score (PPS) for downstream and chemical construction, another industry sector that has a comparable level of complexity to healthcare sector work (2021).

Thus, given that the PPI model was developed on a large dataset of projects (189) and on a variety of institutional projects (correctional facilities, medical research, military installations, engineering science labs, etc.), and that its merit was validated on IPD projects by a separate effort, the researchers and company agreed to use the PPI model (Labib, 2019; Hanna & Morrison, 2021).

The Project Performance Index

Labib's PPI score is as follows (2019):

$$\begin{aligned} PPI\ =& -1.101 \times RFI\ processing\ time - 0.219\ \times Percentage\ change \\ & -0.241 \times Schedule\ growth\ - 0.022 \times Schedule\ factor \\ & -0.014\ \times Number\ of\ RFIs\ per\ millionUSD + 0.011 \times Construction\ speed \\ & +0.67 \end{aligned} \quad \text{(Eq. 1)}$$

An astute reader will note that this equation does not utilize all 15 factors that were previously identified. This is because while all performance metrics identified were relevant to the company's operations and business intelligence needs, not all of them have been found to correlate to project performance, and some (such as company image) are not true quantitative metrics as defined in Table 1 previously. Therefore, they are not weighted or used to calculate the PPI here.

Adding further value to the company's efforts, the PPI score can be scaled into a numeric value between MinR (1) and MaxR (10), which creates a useful and intuitive shorthand for project performance comparison as shown in Equation 2 (Labib, 2019).

$$PPI_{scaled} = \frac{(PPI - PPI_{Min})*(MaxR - MinR)}{PPI_{Max} - PPI_{Min}} + MinR \quad \text{(Eq. 2)}$$

DATA COLLECTION AND CHARACTERISTICS

After the target performance metrics and project scoring strategy had been agreed to, the researchers worked with the company to design a questionnaire that could be circulated to collect the data needed for analysis. The questionnaire was structured to align with similar data collection vehicles that have been used by the researchers over the last decade, to ensure a uniform dataset from which informed and accurate comparisons can be drawn. The questionnaire includes thirteen sections, as follows: Project Characteristics (I), Special Conditions (II), Prefabrication Usage (III), Contracting Strategy/PDS (IV), performance data for communication, change, quality, safety, cost, schedule, labor, and business (V-XII) and contact information for required follow-up questions (XIII). For brevity, the survey is not included in its entirety in this paper. The survey was distributed to the company's corporate offices in major markets across the midwestern United States, from which eleven medical sector projects were gathered. A further twenty healthcare specific projects were supplied from project data maintained at the University of Wisconsin - Madison to provide a database from which to comparatively evaluate PDS performance. Project data from the assembled dataset were plotted using the boxplot, a common statistical tool.

DATA CHARACTERISTICS

The eleven company projects and twenty industry projects that were analysed in this effort were executed between 2007 and 2021 in all cases, and specifically within 2017-2021 for the company's projects. The company data consisted of two IPD projects from their pilot work with the delivery system and nine CMR projects. The industry data consisted of seven IPD projects, and nine CMR projects. While the company did not directly deliver any projects under DBB, the researchers also included four such projects as an additional comparison since the data was available. All datapoints were from projects completed in the United States, with the largest share of projects being completed in Wisconsin (18). Other states represented in the data by multiple projects included Missouri (3), Minnesota (2), Illinois (2), and Florida (2).

The cost data in these projects were standardized for time and location using the RSMeans 2021 historical cost indexes and city cost indices. The reference location and year in this study are Chicago and 2021, respectively. The standardized cost of the projects ranged from $3 million to $661 million with an average of $152 million.

RESULTS AND DISCUSSION

The thirty-one assembled projects were first characterized in terms of key characteristics (cost, location, delivery system, etc.). Then, the projects were analyzed by delivery system chosen and scored using the previously provided PPI equations, as well as for each of the eighteen performance metrics. The PPI scores and a selection of the performance metrics will be presented in this section for comparison and discussion. In each box plot in this section, the result of the pertinent equation defined in Table 1, previously, is plotted on the Y axis. Further, in each case the company's specific project data will be presented in light grey and on the right-hand side of the comparison, while the industry data will be presented in dark grey and on the left.

COST PERFORMANCE EVALUATION AND COMPARISON

The two metrics used to measure cost performance were cost growth and project budget factor. It should be noted that one of the company projects did not report cost data sufficient for analysis and was therefore excluded. Thus, only 30 projects are assessed here. Figures 2 and 3 present the box plots for each of the cost metrics.

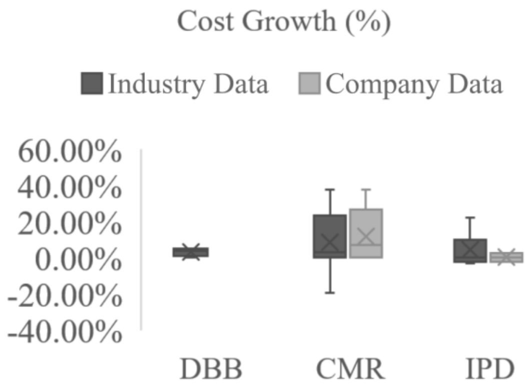

Figure 2: Cost Growth Performance

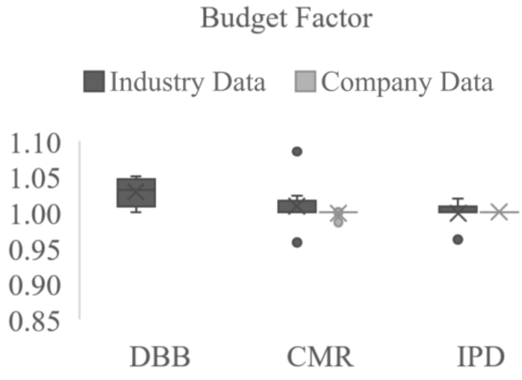

Figure 3: Budget Factor Performance

It is apparent that the projects delivered under CMR by both the company and the industry at large have higher cost growth and a higher budget factor than those delivered under IPD. In comparison to the industry at large, the company's CMR projects have both a higher mean and higher range in cost growth. This implies that the company tended to experience higher actual cost than baseline estimates. However, the same CMR projects had a budget factor quite close to 1, which implies that the majority of the cost growth percentage was due to approved change orders, rather than any degree of poor project performance. By considering these metrics in tandem, the company can ascertain a more impactful picture of its performance than by considering either alone. On the IPD projects that were examined, the company's cost growth was 0%, outpacing the industry data's (4.23%).

SCHEDULE PERFORMANCE EVALUATION AND COMPARISON

Figures 4 and 5, below, present schedule performance as measured by schedule intensity, and construction speed. All projects in the dataset reported sufficient information to be included in the schedule analysis. However, it was found that the company experienced negligeable schedule growth on all its reported projects, indicative of strong operational practice. Thus, the value of visualizing schedule growth for comparison is limited, and the figure is omitted.

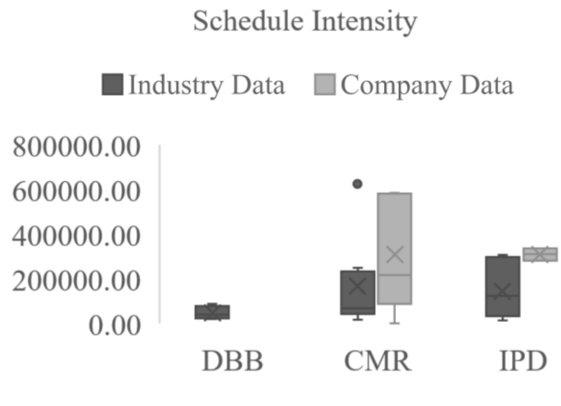

Figure 4: Schedule Intensity Performance

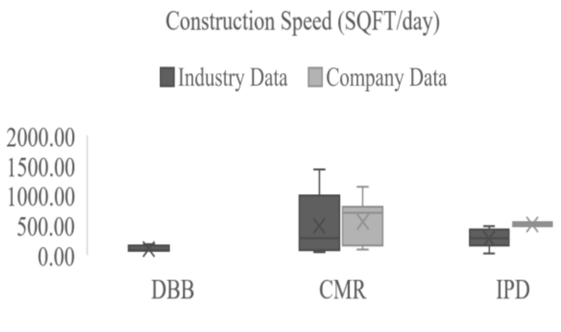

Figure 5: Construction Speed Performance

Both the company's CMR projects and those of the industry at large slightly outperformed IPD projects in terms of construction speed. Additionally, the company's projects under both delivery systems were faster (in terms of construction speed) and more intense than the average. This speaks to corporate culture and project approach in addition to PDS selection.

Encouragingly, the company saw little-to-no schedule growth, regardless of delivery method (the industry by contrast experienced 19.2% schedule growth in CMR and 14.2% in IPD).

CHANGE MANAGEMENT PERFORMANCE EVALUATION AND COMPARISON

Change management was measured in terms of three metrics: change order processing time, absolute project percent change, and percent change ascribable to program, design, or quality. The company's IPD projects experience no change due to design or quality, vastly outperforming both their own CMR projects and the industry at large. However, the specific reason-related percent change comparison is not reported as individual figures for brevity.

Change order processing time, shown in Figure 7, is presented on a 7 point scale: 1 (1-7 days), 2 (8-14 days), 3 (15-21 days), 4 (22-28 days), 5 (29-35 days), 6 (36-42 days), and 7 (greater than 42 days).

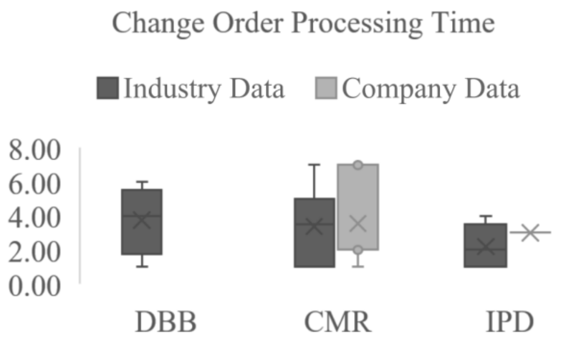

Figure 6: Change Order Processing Time Performance

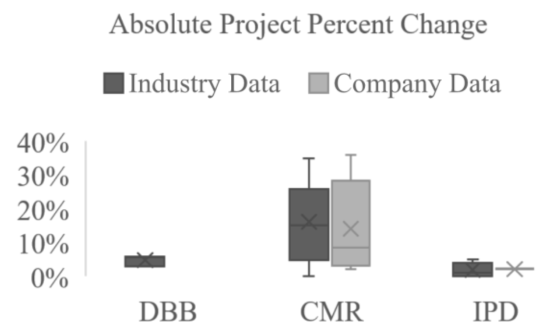

Figure 7: Absolute Project Percent Change Performance

As is evident, the company experienced higher change order processing time for both CMR and IPD than the industry at large. However, it should be noted that change order processing time is frequently beyond the control of the contractor directly. IPD projects for both the company and the industry experienced a lower volume of percent change, as shown in Fig. 7.

COMMUNICATION AND DESIGN QUALITY EVALUATION AND COMPARISON

Similarly to the presentation of change order processing time in the preceding section, RFI processing time is presented on a five-point scale: 1 (1-7 days), 2 (8-14), 3 (15-21), 4 (22-28), and 5 (29-35 days). DBB, as would be expected, has the highest number of RFI per million dollars on average, followed by CMR and IPD, indicative of the increased coordination and design quality that IPD can produce due to more collaboration among the project team and an incentive of a shared risk pool. The company specifically saw higher numbers of RFI per million dollars than the industry at large, and a more variable processing time under IPD.

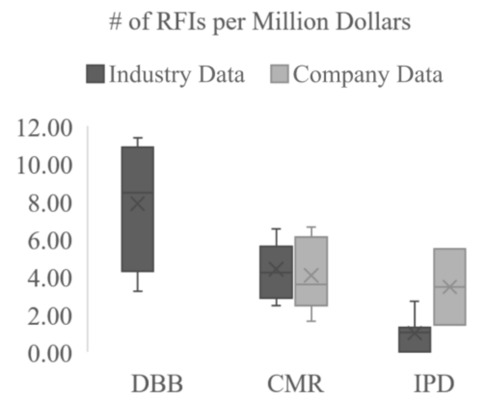

Figure 8: # of RFIs per Million Dollars Performance

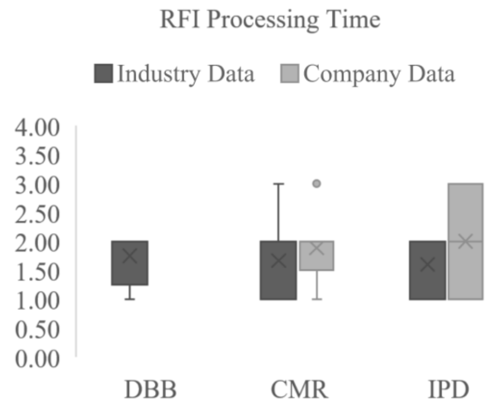

Figure 9: RFI Processing Time Performance

PPI PERFORMANCE EVALUATION AND COMPARISON

The PPI scores from 22 projects[9] were calculated, scaled, and then compared. The results are shown in Figure 18. The performance ranges of the CMR and IPD projects are close. However, the average scaled PPI score of the CMR projects is lower than the IPD projects in general. The company outperformed the rest of the industry in terms of both CMR and IPD projects.

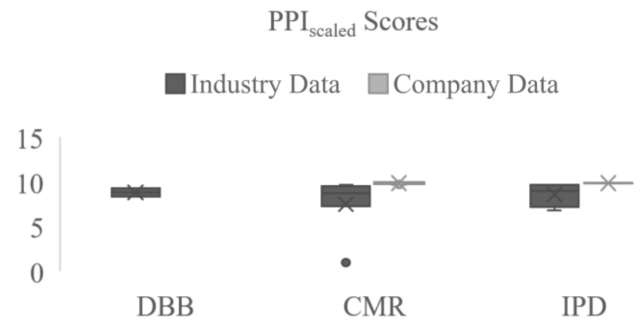

Figure 10: PPI Scoring Performance

DISCUSSION OF RESULTS

The overall performance of IPD projects scored better on the PPI than other delivery systems for both the company's IPD pilot projects and the industry project data. Additionally, IPD was the best-performing on average in terms of: Punchlist items per \$1M, RFI per \$1M, Quality-Related Percent Change, Design-Related Percent Change, Change Order Processing Time, Absolute Project Percent Change, Schedule Growth, Cost Growth, and Budget Factor. This amounts to 64% (9/14) of the assessed metrics (recall that the qualitative metrics, as well as safety, are not differentiators between PDS). The company's consistently better performance than the industry on both IPD and CMR projects is not solely due to the delivery system. The company is a recognized leader in CMR delivery and as such is and was able to realize exceptional performance under that system. This performance is in part due to lean practices that are embedded in the company's culture include use of Building Information Modelling (BIM), the Last Planner system, the Big Room, and others. The researchers believe the company was thus more 'IPD-ready' than it had previously thought and was hence able to realize the benefits that research has long shown IPD can deliver effectively. However, that is not to discount the ability of IPD's risk-sharing, incentivization of collaboration, and multiparty

[9] Sufficent data to calculate the PPI was only available from 22 projects: 2 (9%) DBB, 14 (64%) CMR, and 6 (27%) IPD projects.

strategy to improve communication, design quality, and performance, as was seen in the more expedient processing of changes and reduced amount of overall project change and requests for information, among other performance indicators. The key understanding is that IPD and lean are tied together – lean theory and practice facilitates organizational paradigm shifts, while the IPD system provides an avenue to utilize those lean tools and practices in pursuit of a shared project goal.

LIMITATIONS

As this study was a case-study type examination of a specific company's transition into IPD, it necessarily collected new data only from one company. However, this methodology can be easily adapted to other company-specific examinations, and over time an understanding could be built of the industry's transitions to IPD. For such an investigation to occur, it is likely based on previous work (Hanna & Morrison 2021, Ibrahim et al. 2020, Labib 2019, Antoine et al. 2018) that closer to 100 datapoints would be needed.

Furthermore, this study focused on healthcare sector projects. As a result, findings about the relative performance of the PDS in question may not directly translate to other industry sectors. Again, however, the methodology is sound enough to be applied to other sectors should further researchers wish to do so.

CONCLUSIONS

Thirty-one construction projects from within the healthcare sector were analyzed to assess the performance of a major contractor's transition to IPD in their work. Eleven projects from the contractor were collected (including the two initial IPD pilot efforts) and twenty were supplied from institutional data held by the researchers. Eighteen performance metrics were identified, and fourteen of them were used for comparison (safety, project system quality, and business image were excluded – safety due to its lack of correlation with PDS as defined by previous research, and the other two exclusions due to the structure of the metric being qualitative in nature and therefore ill-suited for comparisons of this type).

The areas in which IPD was the superior performer are logical, given the priority that this lean delivery system places on communication, coordination, change management, scope management, and quality. Specifically, it was found that IPD was the best performing PDS in terms of RFI per million dollars, as well as punch-list items per million dollars, percent change, and change order processing time as compared to CMR. DBB, while included for referential comparison, was not representative, as the company examined did not use the DBB PDS.

Moreover, this paper presents an easy-to-adopt framework for other companies wishing to develop report cards on their IPD efforts to utilize as part of their project scoring. The Project Performance Index (PPI) allows for disparate projects to be compared within a company and across the industry. As an ancillary benefit, performing this type of analysis will encourage contractors to begin tracking more project data (if they do not do so already) which will improve their own outcomes and allow for more detailed research in the future.

Most importantly, the researchers were gratified that the results of this comparative effort included an enthusiastic reception to the IPD pilot projects the company had embarked upon and an intention to pursue more work with this contracting strategy in the future. Given that contractors must be selective about what they bid on, identifying IPD as a differentiator that points toward a more successful project is a valuable insight for this contractor and for other industry practitioners, who can easily apply this method to assess and monitor their own IPD implementation efforts.

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COLLABORATIVE DIALOGUE DURING THE PRE-TENDERING PHASE TO MAXIMIZE PROJECT VALUE GENERATION

Valeria Vecchio[1], Abbey Dale Abellanosa[2], Bernadette Konwat[3], Yu Wei[4], and Farook Hamzeh[5]

ABSTRACT

The construction industry has widely adopted traditional project delivery methods, such as design-bid-build, to develop conventional construction projects, where only one main contractor is granted the project contract. Selecting only one main contractor for the project results in the waste of valuable ideas coming from the rest of the bidders who participated in the tendering process but did not win the bid. These ideas, coming from the contractors that lost the bid, are usually not considered during the project execution, even though they could increase the value of a project, shorten the schedule, and reduce costs. As an alternative to solve the current gap of lost creativity and ideas coming from contractors that were not awarded the project contract, this study will explore the workarounds to promote partnership between key stakeholders during the pre-tendering phase by involving multiple contractors instead of a single construction project, to develop innovative ideas that could maximize the value of a construction project. The importance of collaboration and co-creation of value is widely emphasized in lean construction. Experts in the construction industry with a background in collaborative delivery were surveyed and interviewed to understand their opinion on the proposed topic. The experts from both backgrounds concluded that involving multiple contractors instead of just one main contractor is a feasible idea, but it will take effort from all the stakeholders to compromise on this type of agreement. The benefits and constraints of implementing collaborative dialogue are further discussed in the following sections of this study.

KEYWORDS

Value generation, project definition phase, key stakeholder engagement, procurement strategy

INTRODUCTION

Traditionally, the construction industry strives to deliver a construction project that complies with a pre-established schedule at the lowest cost possible. Current practices such as Lowest-Cost Procurement and Design-Bid-Build allow the owner to select a single contractor based

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only on the total cost of the proposal, which leads the client to choose the lowest-cost option out of all the bidders, without considering important aspects such as qualifications, quality, and added value for a project (Nguyen et al., 2018). In addition, the competitive nature of the current procurement methods, where only a single contractor is granted the contract, results in wasted creativity and a lack of innovative ideas from other bidders that could have added significant value to the proposed project, but will not be applied since these contractors were not awarded with the contract.

Recently, the construction industry is leaning towards a more collaborative work strategy (Mosey, 2019), where methodologies such as Design-Build (DB) and Integrated Project Delivery (IPD) are being implemented (Maturana et al., 2004; Tillmann et al., 2017). Procurement strategies like Best Value (BV) and Competitive Dialogue (CD) allow the owner to select a contractor based mainly on proposals that could add value to the project. However, this does not solve the wasted creativity issue that results from choosing only one contractor and not using the innovative ideas coming from other contractors.

As an alternative to resolving the previously mentioned gap, this study proposes the idea of a collaborative dialogue where multiple contractors can be involved in one single project. This would be achievable by combining the BV and CD into a single collaborative procurement. The methodology would follow an initial pre-selection phase that would allow the client to choose the contractor that best aligns with the project they want to develop. After the pre-selection, the owner would have a dialogue with the pre-selected contractors to allow the flow of ideas between stakeholders to improve the current project design and share suggestions that could add more value to the construction before the execution (Wondimu et al., 2018). The several contractors would be compensated just for passing to the dialogue phase, and in case they offer ideas that add value to the project, they would be compensated for them or even hired as consultants for the project, working collaboratively with the awarded contractor. The early contractor involvement (ECI) and flow of ideas between different professionals would open a space for innovation that could lead to cost and time-efficient projects (Nygård et al., 2019; Tillmann et al., 2017). Moreover, advantages and disadvantages of collaborative dialogue are explored through expert interview that is discussed in the results and discussion section.

LITERATURE REVIEW

The procurement phase in construction is defined as a pre-tendering stage in which roles, risks, and responsibilities are identified and assigned among all construction project stakeholders (Ying et al., 2021). The chosen procurement strategy specifies how the interested parties will collaborate to meet the client's specifications regarding a construction project (Wondimu et al., 2018).

Traditionally, the Lowest-Bid Procurement has been selected as the most popular option to choose the AEC team. In the Lowest-Bid alternative, the client selects the contractor based only on the total cost of the proposal, which leads the client to choose the lowest-cost option out of all the bidders (Nguyen et al., 2018). The procurement method has the benefit of allowing the owner of the project to choose the most economical option out of all the bids, but it overlooks important aspects such as the qualifications of the personnel, and the quality of the product, and might lead to conflict due to misalignment of interests and the lack of a clear definition of what value is for the client and the contractor (Nguyen et al., 2018). The last two effects usually make the project prone to suffering schedule delays and cost overruns project (Wondimu et al., 2018). Multiple studies suggest that collaborative approaches such Target Value Design (TVD) and Integrated Project Delivery (IPD), as alternative to the traditional tendering methods, can be integrated into the procurement phase to meet the needs of the project (Mosey, 2019; Musa & Pasquire, 2020; Whelton et al., 2004).

To reduce the chances of misaligned interests and effectively define value as the main objective of a construction project, an alternative to Lowest-Bid Procurement has been developed, known as BV (Nguyen et al., 2018). This procurement method attempts to choose the best AEC team based on what the client considers to add value to the project rather than the low price of the proposals (Ying et al., 2021). Moreover, BV procurement allows for the early involvement of the contractor in a public construction project (Nygård et al., 2019). The procurement method has commonly been used to minimize the involvement of the client during the design and execution phases of the project since the contractor is considered the expert and the only member capable of making decisions related to the development of the construction project (Wondimu et al., 2018). Multiple studies have reported (Lesjø et al., 2019; Nygård et al., 2019; Tillmann et al., 2017; Whelton et al., 2004; Wondimu et al., 2018) that, even though BV focuses on ensuring both value and lower costs before construction starts, there is still conflict and misalignment between the owner and the contractor about these aspects during the execution phase of the project. Furthermore, misalignments of commercial incentives in AEC projects can be avoided if participants select trusted and competent members; business models and key performance metrics is communicated well; stick around to adapt towards the principles of IPD and TVD; ensure that participants are adequately trained in lean construction; and adequate resources to implement IPD and TVD systems (Do et al., 2015).

Ying et al. (2021) conducted qualitative research on BV procurement in New Zealand, interviewing project managers, designers, engineers, and procurement specialists to explore ways to increase innovation and improve the system. The results suggest that innovation can be achieved by promoting a mindset shift among stakeholders and enhancing communication and collaboration throughout the procurement process to achieve the common goal of creating a project with the best value for the client. On a different study, Malvik et al. (2021) evaluated the performance of Best Value (BV) procurement in a public highway construction project, using Integrated Project Delivery (IPD) as the project delivery method. The study attempted to combine BV and Target Value Design (TVD) to improve collaboration among stakeholders. However, the results showed that a lack of transparency in managing the bill of quantities (BOQ) by the contractor and a lack of shared responsibilities during decision-making created conflicts and hindered efficient collaboration between the client and contractor. Since collaboration seems to be one of the root problems during the procurement phase, even with more progressive methods such as BV, other alternatives have been developed to stimulate shared responsibilities and the flow of ideas among interested parties to create a more valuable project.

CD is a procurement approach where the client narrows down potential bidders through pre-qualification, allowing for dialogue and idea exchange to optimize the project and gain more value before officially choosing the contractor (Wondimu et al., 2018). Both Best Value (BV) and CD consider value and price while selecting the AEC team, but CD allows the client to discuss ideas with multiple contractors before deciding on the best option, while BV only clarifies the project's scope and work strategy after selecting a single contractor (Wondimu et al., 2018). Both CD and BP procurement approaches were compared to each other during a research study where the participants of two different highway construction projects in Norway applied both procurement methods to improve the collaboration between client and contractor (Wondimu et al., 2018). The study included face-to-face interviews with executive managers from both sides of the contractual agreement. The results proved that BV and CD allow space for ECI thus, improved collaboration can be achieved in the two procurement strategies (Wondimu et al., 2018). However, pre-selection and dialogue in CD are time-consuming but increase the likelihood of selecting a contractor offering the best value, and optimize the project's original concept (Wondimu et al., 2018).

Wondimu et al. (2018) in essence considered that the key to improving collaboration between the stakeholders of a project stands in the pre-qualification and dialogue steps that are part of the CD. The pre-selection phase allows the client to choose the contractor that best aligns with the project they want to develop, and the dialogue phase allows the flow of ideas between the client, several contractors, and other interested parties to improve the current project design and share suggestions that could add more value to the construction before the execution (Wondimu et al., 2018). Currently, CD only chooses one of the interviewed contractors from the short-list as the construction manager for the project, but an alternative to increase even more collaboration in DB projects and reduce the waste of time for the contractors that were not selected includes that the client compensates the contractors that were selected for the short-list for their participation while hiring contractors with clever ideas for the project as consultants. The disadvantage of this alternative is that it implies additional costs for the client, but the advantage is that there is a possibility that each interviewed contractor comes up with an idea good enough to significantly improve the design and execution strategies for the project, which will result in a more valuable project by including collaboration from all the stakeholders (Wondimu et al., 2018). Although the previously mentioned studies provided valuable information about collaborative procurement, none of the studies addressed how the relationship between multiple contractors would work in a collaborative procurement scenario. Further studies need to be conducted to test this theory, which will be the focus of research for the present paper.

METHODOLOGY

A comprehensive review of previous literature and studies on different procurement methods and project delivery methods will be done to identify the criteria and methods used during the pre-tendering phase and contractor prequalification. The literature review will be used to develop theoretical background on the topic and explore the current problems and issues faced in the current industry methods. Backward and forward snowballing methods will be used to not miss out on both new and old reference papers (Lesjø et al., 2019).

The research method was a mixed-method approach of quantitative and qualitative data collection (Roopa & Rani, 2012). A survey questionnaire was developed and sent to professionals in the AEC industry and gathered data from over 50 respondents. The respondents needed to have at least 5 years of experience, be actively working in the construction industry and needed to have a basic knowledge of collaborative project delivery methods. The respondents must be working under these construction disciplines: design architects, engineering consultants, contractors, and subcontractors. Respondents were from different countries such as Canada, Singapore, the Philippines, and Egypt. The questionnaire was formulated using close-ended questions where respondents were limited to a fixed set of responses and scales are closed-ended.

Lastly, to validate the survey results, interviews were conducted with 2 experts on the collaborative delivery approach and best value practices in the industry. The first interviewee is an experienced land developer in Canada and the second is a construction veteran in the Philippines. Interviews conducted were done through in-depth semi-structured interviews via video conferencing and are recorded and transcribed. A concurrent triangulation strategy is used to compare the survey results and interview responses gathered to determine any confirmation or disconfirmation. This approach will be used to first provide quantitative statistical data and then validate or invalidate based on the quantitative interview.

SURVEY RESULTS

A total of 57 respondents were gathered. Out of the 57 respondents, 43.9% are from the main contractor background, 33.3% are from the Architect/Engineer/Consultant side, 12.3% are owners/developer experts, and 10.5% of the respondents are subcontractors. The distribution of respondents' years of experience is shown in Figure 1. This figure tells us that there are more professionals who have relatively less years of experience. The respondents' work experience in the industry ranges from 5 to 50 years and the designations were owners, architects, project engineers, planning engineers, M&E coordinators, quantity surveyors/estimators, associate directors, and directors, vice presidents, and senior project managers.

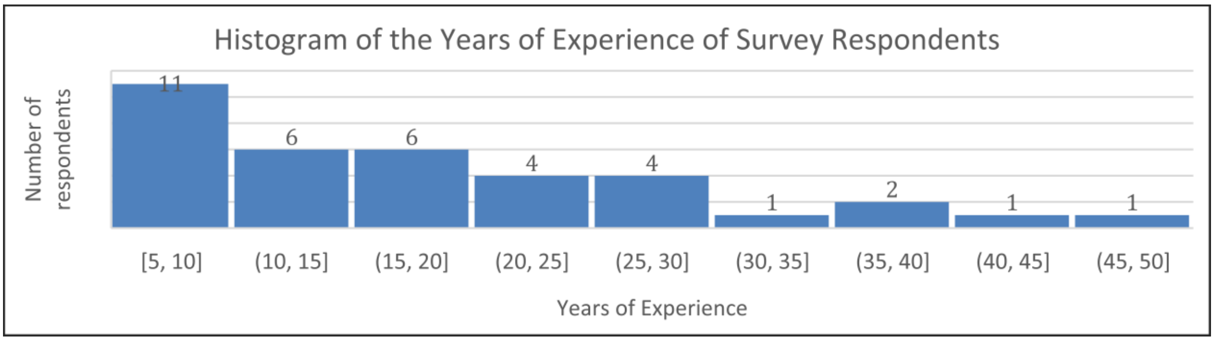

Figure 1: Histogram of the Years of Experience of Survey Respondents

The survey started with questions regarding the role, position, and years of experience of the respondents in the construction sector. By asking these questions, it was easier to identify if the respondents met the criteria to be qualified as participants in the present study. After the introductory questions, participants were asked about their previous experience in collaborative procurement (working with several stakeholders during the pre-tendering phase). The results showed that most of the respondents have experience in collaborative procurement (71.9%) and only 28.1% have not experienced collaboration during this phase of the project. Likewise, 61.4% agreed that collaboration during the pre-tendering phase improves the selection of the AEC (Architect, Engineer, and Contractor) while only a small percentage disagreed (1%). More than 90% of the respondents also agreed that collaborative procurement improves the overall delivery of the project, not only during the pre-tendering phase.

The survey was then divided into two sections, questions about collaborative procurement from the owner's point of view and then from the contractor's point of view. The objective behind this idea was to allow all the participants, regardless of their role within the industry, to think of how collaborative procurement would work from two different perspectives. Some of the questions were designed to be yes/no questions, while others provided additional space for the participants to give their input on the information they were being asked about.

GENERAL PERSPECTIVE

As a more general question, the respondents were asked to rank on a scale of 1 to 5, how hard they think the collaboration or cooperation during the pre-tendering phase could be; with 1 being very easy and 5 as very hard and almost impossible. Only 7% of the respondents believe that it would be almost impossible, and about 52.6% of them believe it to be just at the halfway point, not too easy and not too hard. A summary of the result is shown in Figure 2. Regardless of their role in a project, 96.5% of the surveyed respondents believe that having a dialogue about possible optimal solutions for a project, instead of just a clarification phase before signing the contract, would reduce the chances of conflicts between stakeholders and add more value to the project.

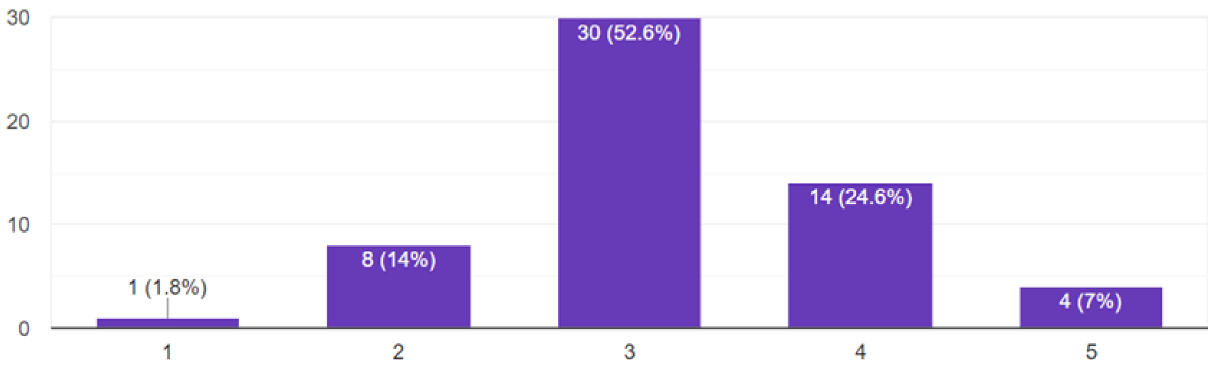

Figure 2: How Hard to Implement Collaboration (1 very easy and 5 very hard)

Owner's Perspective

From the owner's point of view, the results show that almost 90% of the respondents are willing to have a dialogue with several contractors before choosing the most suitable team for the project. However, one respondent highlighted that he will either go with the contractors he is most familiar with or with contractors recommended by people he trusts or from people in his circle. Similarly, if an idea comes from a contractor, who will not be the awarded contractor of the project, 87% of the respondents will consider using the idea if it adds value to the project, but only 63% of the participants are willing to pay for the idea. About 26% of the respondents do not agree to pay for the idea obtained from other contractors and the rest highlighted that it will depend on other factors to be considered such as the cost of the idea, if it is proprietary or not, and if it is an innovation or just an industry standard.

In addition, most of the respondents (74%) are willing to hire the contractors, who were not awarded the project but contributed value-adding ideas, as consultants for the project. However, some participants believe that not all contractors with brilliant ideas can execute their theory properly and that their performance would depend on the scope of the project.

Contractor's Perspective

On the other hand, from the contractor's perspective, almost all (94.7%) of the respondents are willing to have a dialogue or discussion with the owner before signing the contract, despite not being certain about their future participation in the project. The survey results indicate that most of the contractors, 86%, do not get any form of compensation from the owner for losing a bid. The participants manifested, from the contractor's point of view, that 93% of them are willing to participate in the bid process knowing that there will be compensation for participating and giving value-adding ideas to the project. Moreover, 65% of the participants are also willing to be hired as consultants for the project despite not being awarded the contract.

INTERVIEW RESULTS

To validate the results from the survey, and based on the responses of the participants, two interviews were arranged to ask more questions about collaborative procurement, one with a Developer/Owner expert and another one with an experienced Contractor. Some of the questions were the same as the ones provided in the survey, but the interview experience allowed more space for short explanations after every question. In addition, the interviewers were asked about their opinion on the advantages and disadvantages of paying multiple contractors, who were not granted the contract award, for their value-added ideas, and we also asked the experts about their input in hiring several contractors as consultants for a project.

EXPERT VALIDATION (OWNER / DEVELOPER)

The first interviewed expert works as a Vice-President of Development in Edmonton, Canada. He reviews and takes a lead in design directions, manages approvals with the city of Edmonton, and oversees the Construction Managers' work on several projects. He has over 20 years of experience working in the construction industry.

When asked about the popularity of collaborative project delivery, the expert mentioned that there has been an increased interest in this type of delivery method in the last four years due to its economical effectiveness and cooperation between stakeholders throughout the design and execution phases of a project. He mentioned that he had experienced the successful results of collaborative projects himself when his company was able to save $300,000 because of collaborative meetings, where all the stakeholders were able to participate in the decision-making process of a water project after a conflict with one of the suppliers of a pipeline had arisen.

When choosing an AEC team during collaborative procurement, the expert highlighted that he would feel more comfortable working under this type of procurement with a contractor he has previously worked with and has known for many years. In case he is required to seek a new contractor, he would set up an interview to get to know the contractor on a personal level and would do a background check to verify the level of expertise of the contractor and his availability to handle the costs and risks related to the scope of a project.

When asked if he had previously used input ideas of different contractors on a construction project without granting them the contract, the expert said that he had done it before, but not without compensating them for their input. He mentioned that he has hired other contractors, different from the main contractor, as consultants for his projects.

The interview was finalized with advantages, disadvantages, and recommendations about paying different contractors for their ideas and hiring them as consultants, instead of just having one contractor for a project. Among the advantages, the expert mentioned that collaborative procurement has proven to be economically efficient, and the teamwork environment makes the project an enjoyable social experience. When asked about the disadvantages, he mentioned that the relationship between contractors is extremely competitive, and it would be very difficult to make them work together as a team, since conflicts and disputes between them would be very likely to occur. One of the recommendations he suggested is to make the stakeholders and different contractors share what is known as the profits and risk pool. This means that the contractors should be rewarded proportionally for their involvement in a project and the profitability of their ideas. Similarly, in case of financial losses, contractors should take accountability for their actions based on their level of involvement in the event.

EXPERT VALIDATION (CONTRACTOR)

The second interviewed expert has over 40 years of work experience in design, construction, risk management, and project management. He was the former President and CEO of a major construction company in the Philippines specializing in industrial, infrastructure, and specialty works. He is currently the President and CEO of another construction company specializing in mid to high-rise commercial and residential buildings.

Through his work experience, he pioneered early contractor engagement in Philippine power plant projects. He explained that by engaging contractors early, they did not need to wait for drawings to be prepared which saves the total project duration by almost 2 months. Projects were approached like an open book and other stakeholders were treated as partners. However, there will still be a consultant engaged to do the checking and inspection. Every stakeholder shares the risk of quantities but there is also a guaranteed margin of around 15% to 20%, discussed and agreed upon before the collaboration.

When asked what type of projects are more suitable for collaborative delivery, he mentioned that in the Philippines, most PPP projects are already engaging early contractor involvement. Owners now do not go for bidding because, from the time the project is conceptualised, the approvals almost take 3 years. Aside from PPP projects, there is still much hesitancy in collaborative projects, mostly due to owners rather than contractors. From a contractor's point of view, there is no loss in being engaged early because it entails the assurance of a project.

Collaborative procurement has advantages such as saving time and costs for the owner. He explained that contractors can provide more options to the owner, not only based on cost but also on choosing the better methodology. Methodology drives the price. Some designers design specifications that are not available or feasible. By engaging the contractor early on, specifications can be agreed upon with the owner and there will be fewer variations when the project starts.

In another follow-up question, he asked a contractor if he would be willing and if it is possible to collaborate with another main contractor. He agreed it is possible and that they have done it before. They had a previous joint venture with 2 other biggest contractors in the Philippines. "We derive strengths where we are weak", he quoted. In previous experience, since his company is good in electromechanical works, but another main contractor is good with civil works, they collaborated and had a successful project.

The interviewers then asked how tough will introducing collaborative procurement and project delivery be, especially since traditional contracts are competitive instead. Usually, when the competitors rely on a subcontractor to do the work, it means it is not their core competency. Instead of you winning alone, you can suggest joining together, sharing the loss and profit. That is where consortiums come in. However, this can only happen with "mature" contractors. "If you want us to be stronger than the rest, let us combine forces and bring value in different ways", he quoted.

Regarding compensation for contractors contributing ideas, there should be reasonable compensation depending on the level of engagement. If they cannot add value to the contractor company, it is better to accept the compensation rather than join the project and contribute to the waste. According to him, the biggest challenge in this type of delivery is getting the owner to participate willingly in this kind of collaboration and early contractor engagement. If the client is willing to do it and the contract agreement is fair, the contractors will always want to do the work.

To wrap up his final thoughts, he concluded by highlighting that the more owners and contractors adopt the idea, the more benefits they will reap on time and costs and there will be fewer issues, disputes, and arbitrations. Arbitrations put a stop to the beneficial use of the projects. People can do more important things than attend to disputes. If the big industry players will start to adopt this kind of procurement, the advantages are very clear, it saves time and cost. If there is mutual trust, we can eliminate cheating and corruption which is rampant in the construction industry in any country. To be able to do repeat engagements, one cannot cheat. It has more advantages than disadvantages. Once more people accept the idea and become more open to exploring it, they will realize it is all advantageous rather than disadvantageous.

RESULTS AND DISCUSSION

Both the survey questionnaire and the interview results exhibit that there has been an increased popularity of collaborative procurement in recent years. Though this collaborative procurement comes with its own advantages and disadvantages as summarized in Table 1. The results from the survey questionnaire showed that there is a high willingness from contractors and owners to engage in a dialogue before awarding a contract, to discuss project ideas, and elevate the relationship to a more personal level to increase trust among the involved stakeholders, an indispensable element in collaborative projects. Moreover, the survey shows that owners are open to having a dialogue with multiple contractors and using their ideas if it is considered that would add value to the project, even though the ideas are not coming from the awarded contractor.

Table 1: Summary of Advantages and Disadvantages of Collaborative Procurement

Advantages	Disadvantages
Share technical best practices between the owner, designer, and contractor.	The contractor becomes involved in the project before it has been designed in detail and may not provide an accurate price for the construction works.
The earlier the contractor is identified, the greater the potential benefits the contractor can bring to the project.	Traditional contracts generally provide elements of transparency and competition. In early contractor engagement, other contractor bidders could lose interest in the project since the early-engaged contractor will have a competitive advantage.
Well-defined scope of work and target price at completion of conceptual design and fewer potential scope gaps	Conflicts and disputes may occur if there are too many experts in the project.
Owner, designer, and contractor collaborate to achieve goals on overall project cost & schedule; less risk of claims and variation orders from the contractor.	Some great ideas during the pre-tendering phase cannot be executed well.

As supported by experts' personal experience, collaborative procurement was also sought to be both cost and time-efficient and contributed greatly to the success of projects. These findings are in support of the ideas for collaborative procurement under lean construction theory as discussed in the studies of Gomes & Tzortzopoulos (2020) and Malvik (2022). The challenge, based on the owner's point of view, contractors are the ones who may not be willing to participate in early collaboration, which was the opposite of the contractor's point of view. Contrary to owners' belief, contractors consider that there is no loss in being engaged early in the procurement phase because it ensures that they would be part of the construction project. Study results also show that there is no problem with contractors working with multiple other contractors. However, due to the culture of competition in the construction industry, conflicts between multiple contractors during execution are likely to occur. This would represent a challenge for collaborative procurement in the present practice in construction.

Some suggestions from the owner and contractor's perspective are to share profits and risks between stakeholders, follow an open-book accounting format, and offer a guaranteed margin to the contractor for their involvement or consideration in a project. In addition, hiring other contractors, different from the awarded contractor, as consultants or paying them for their ideas have been done before and is possible if it gives benefits to both parties. Contractors are willing to contribute their ideas early in the project planning phase if they will be well compensated for their value-adding ideas. Compensation should be proportional to the level of involvement and application of the ideas of the contractors because some ideas cannot be executed well.

CONCLUSION

Collaborative procurement can only be achieved if all the stakeholders work together towards accomplishing the objective of adding value to a project. Following lean principles is key to ensure an efficient collaboration between stakeholders towards a common goal. Project owners could be initially hesitant to reward multiple contractors for their bidding participation and valuable ideas since it represents a financial increase in the overall project cost. However, financial compensation motivates stakeholders to work as a team and create beneficial ideas for the projects to achieve a common goal. Antagonistic behaviors within the project team should be avoided, and conflicts should be resolved with the sole purpose of optimization and continues improvement, which are essential lean principles. Additionally, the early involvement of the partners in selection process increases the chances of building a well-functioning team (Tillmann et al., 2022). Early stakeholders' involvement provides the opportunity to work on the expected project quality through open and continuous communication, resulting in lower costs and a reduced schedule for a construction project.

In conclusion, collaboration and early contractor involvement are dependent on the accurate application of lean principles for the method to work. Stakeholders are required to work as a team to increase innovation and efficiency in construction projects. Including key participants of the project in the early design phase results in shared knowledge and continuous improvement, reducing the occurrence of common mistakes during the project execution phase, such as the case of project delays. Each participant is rewarded for their value-added ideas, which motivates contribution and flow of ideas within the team.

As demonstrated in this study, owners, A/E, contractors, and other trade partners are mostly open to the idea of collaboration in the pre-tendering phase to improve value during the execution of the project, as it is already a technique that has been widely used in many countries. The method still needs improvement, but industry practitioners who have already experienced this kind of collaboration consider the method as time efficient. The interest in collaborative procurement could further increase if proper compensation, proportional to the ideas contributed by the contractors/trade partners, is stipulated before the bidding for a construction project. This study mentions that trust between contractors could be a difficult aspect to resolve during collaborative procurement.

Further research should be conducted to investigate solutions to this problem. Additional research could evaluate the impact of applying open book approaches for collaborative procurement and alternative methods to deal with conflict between stakeholders in case of a collaborative contract. Moreover, evaluating contract pricing for added value for ideas is an area that could benefit from further research. Research on this topic could explore ways to incentivize contractors to offer innovative and value-adding ideas by incorporating performance-based incentives in the contract pricing. This could include mechanisms to measure and compensate for the added value generated by these ideas, such as a share of the cost savings or additional revenue generated.

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TOWARDS A FLOW-BASED DISRUPTION METRIC: A CASE STUDY

Eran Haronian[1] and Shmuel Korb[2]

ABSTRACT

Construction projects are inherently ad-hoc, meaning if disruptions arise, it can be hard to quantify the impact of the “damage” that has been done to the cost or timeline as a result of the disruption, as there isn’t necessarily a nominal steady-state condition to compare it to. In this paper, we present a case study of an infrastructure construction project that was beset by over a hundred documented disruptions due to a politically charged project that had ongoing, active attempts to interfere. Traditional approaches to quantifying the impact of disruptions presume there is a baseline against which the disruptions can be compared, which is not the case in a unstable project. Also, they are inherently “transformation” in their approach, whereas a Lean Construction approach would recognize the importance of taking a more holistic view incorporating elements of Flow and Value. A WIP-based metric of the project outcome, called “WIP-Time” is proposed and assessed in the context of the case study.

KEYWORDS

Disruption analysis, Transformation-Flow-Value theory, contract disputes, production control

INTRODUCTION

Construction projects have long suffered from inefficiencies, leading to cost overruns and schedule delays (Egan 1998). When problems occur, project stakeholders (owners, project managers, contractors) naturally want to understand their nature, so that responsibility can be apportioned and parties “made whole” through compensation. To this end, the Society of Construction Law (SCL) publishes a “Delay and Disruption Protocol” (Society of Construction Law 2017) that is a widely-used framework for mediating disputes between the parties that may arise due to deviations from the agreed project scope.

The SCL defines a disruption as “a disturbance, hindrance or interruption to a Contractor’s normal working methods, resulting in lower efficiency” (Society of Construction Law 2017). Disruptions are distinct from delays, though the two are linked and often lead one to the other. In this approach, disruption events are identified and quantified, using methods like the “measured mile analysis” (Ibbs and Liu 2005). In a measured mile analysis, periods of undisrupted work (the eponymous “measured mile”) are compared to those suffering disruptions to assess the impact of the disruption event on the productivity of the work.

Underlying the measured mile analysis (and the other methods proposed by the SCL) is a transformation-centric paradigm. In Koskela’s Transformation-Flow-Value theory (Koskela 2000), there are different approaches to conceptualizing and understanding production, of which the transformation approach is but one. The Delay and Disruption Protocol makes frequent references to work efficiency, lost productivity, and analyzing direct and indirect costs. All of these clearly indicate that they are solely focused on the actions of transforming the raw

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materials into finished products, which in turn implies they are not taking into account the Flow (how the products flow through the production system) or Value (how the value is created for the end customer, and conversely which elements do not add value and thus are waste) approaches.

In this paper, we present a case study of a project that had over a hundred disruptions, as well as a preliminary metric based on integrating Work In Progress (WIP) in order to assess the impact of the disruptions on the flow of the project and the capability of the project to generate the planned value. While there are Lean-related metrics that have made great improvements upon metrics like the measured mile, such as the Percent Plan Complete (PPC), used in the Last Planner System to evaluate the ability of the team to meet their weekly commitments (Ballard 2000), or the Construction Flow Index (CFI), which quantifies the quality of the production flow (Sacks et al. 2017), these were not found to adequately address the need of quantifying the impacts of disruptions on the project outcome.

PROJECT BACKGROUND

The case study project is a linear infrastructure project (a new rail line) that expands over 20 km, with a cost scope of US$200 million. The general work sequence for the project is presented in Figure 1. In the first stage, structural linear elements such as retaining walls were built (tasks A, B, and C in Figure 1) in parallel with the construction of structural elements in particular locations, such as bridges and tunnels (tasks D and E). After the structural elements, the superstructure of the transportation infrastructure was built (task F), followed by systems and finishes (task G), and handovers (task H). From an engineering point of view, this project was not particularly innovative.

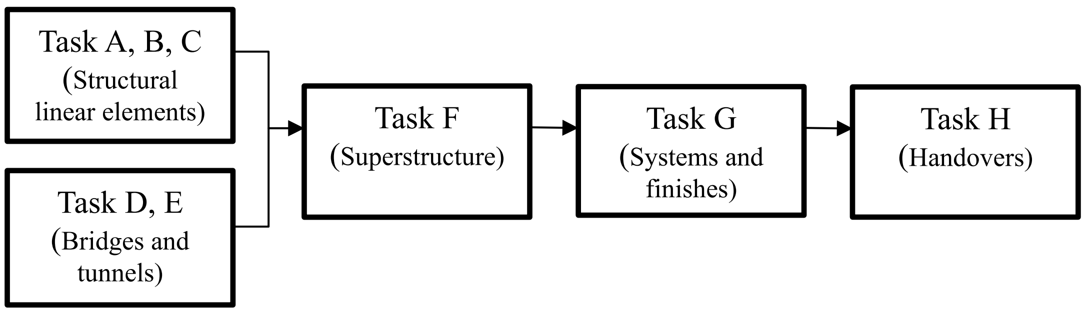

Figure 1: Process sequence for the infrastructure project

While this sequence seems fairly straight-forward, in practice, the project was subject to over one hundred documented disruption events in less than a year. These disturbance events were all caused by external parties, who were attempting to actively interfere with the project. The project was politically controversial, leading to objections, and it became a lightning rod of sorts through which political frustrations were vented through attacks on the project.

The disruption events recorded by the contractor, and categorized based on which type of "waste" (Ohno 1988) they caused:

- Disruptions leading to re-work: damages were caused to the product, as a result trades were required to return to previously-completed sites to perform repair or do the work again. For example, off-road vehicles were driven over graded substrates that had been smoothed and awaiting the next course. The tracks left by the vehicles meant the material had to be re-graded, effectively doing the work again. In other instances, sewage was routed into the work sites, which required drying them out and possibly disposing of contaminated materials.

- Disruptions leading to waiting and transportation: materials (such as steel) and equipment (such as concrete forms) were stolen. As a result, the workers would have to wait for a renewed supply, either from external suppliers or by additional transportation on of the materials within the project (and given the 20km extent of this linear project, this could be quite far).
- Disruptions leading to movement: in general, as WIP levels increased due to the disruptions preventing the closing out of work areas, trades were required to move back and forth from one location to another as they addressed the problem areas. In addition, due to damages to access roads to the site, work trades were sometimes required to travel via alternate (longer) routes. Finally, the project sites were used as illegal dumping sites for construction and other wastes, requiring the removal of more than a hundred thousand cubic meters of waste that had been deposited on the work sites.

While individual disruptions (like theft) might not be clearly political, their high rate of incidence relative to other similar projects made it clear that there was additional motivation beyond random opportunism. The impact of all of these disruptions was to greatly delay the completion of the project tasks, and as a result the entire project suffered, as well. Figure 2 and Figure 3 show the time-location diagrams of one section of the project, with each task shown as a diagonal line. Note that a time-location diagram, which is common in infrastructure projects, has swapped axes from a Line-of-Balance chart (Kenley and Seppänen 2010): time is on the y axis, progressing downwards, and the project locations are on the x axis. The actual project delivery took significantly longer for all tasks to be completed, due to the multitude of disruption events. In Figure 3, the disruptions events for 2022 are shown as small stars (those from earlier in the project were not sufficiently recorded), 120 disruptions in all during the period of a year. As the project (railway construction) was well-understood and relatively routine, it was clear that the disruptions were the cause of the delays, particularly when compared with similar projects that were not subject to the same barrage of disruptions.

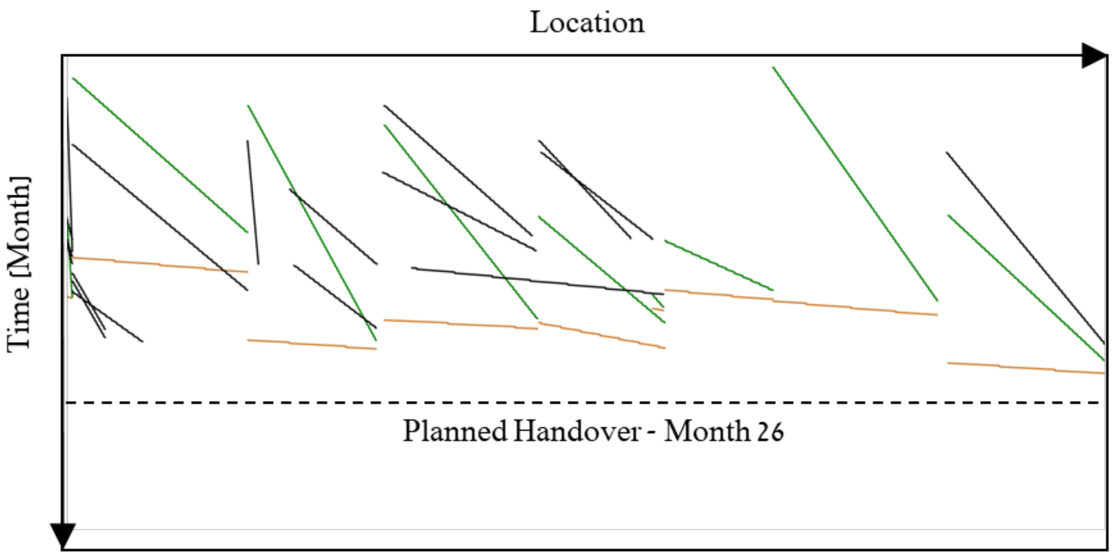

Figure 2: Time-location diagram of the planned schedule for one section of the project

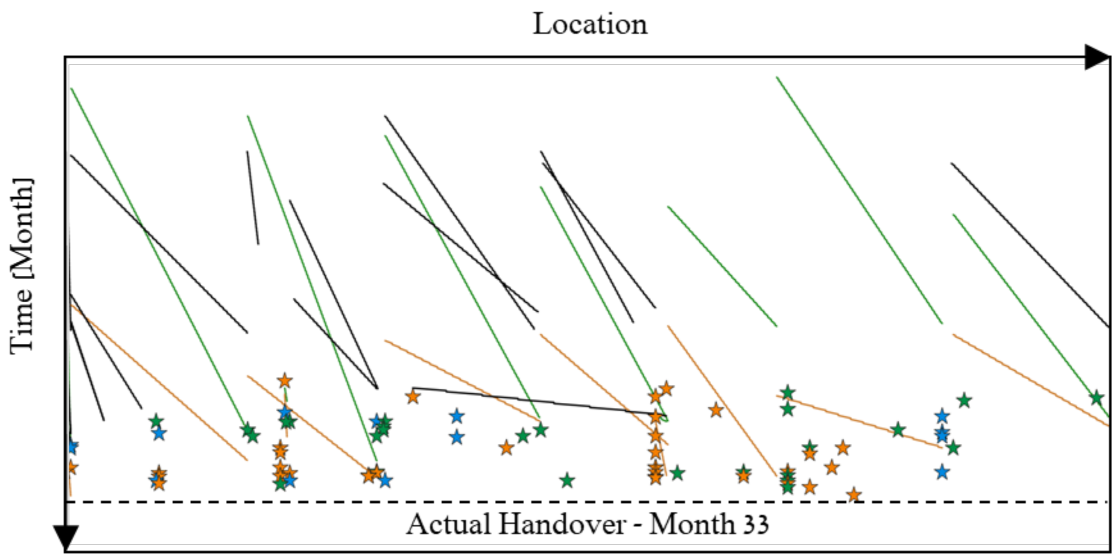

Figure 3: Time-location diagram of the actual schedule for one section of the project, including the 2022 disruption events (show as stars)

Table 1: Legends for Figure 2 and 3

Task/ Disruption	Legend
A, B, C	
F	
G	
Defects, Rework	
Waiting, Transportation	
Motion	

The picture in Figure 4 illustrates the scale of just one of the disruption events that the project encountered.

Figure 4: Illustration of one of the disruptions to the project

A FLOW-BASED METRIC

LIMITATIONS OF EXISTING APPROACHES

As mentioned above, each of the disruption events was documented, using the SCL approach of trying to quantize the financial damage caused by each of the disruptions. For example, in the case of stolen material, the replacement cost of the material would be presented, or in the case of damage, the cost of the workers' time to repair the damage. But a harder question to answer remains what the impact on the overall project is of each individual disruption event.

For example, the missing material could mean that the work for a particular segment of the work would not be able to commence. So either the workers would be underutilized, or they might engage in "making do" (Koskela 2004), which could lead to further waste. And when the material does arrive, the tradespeople have to be scheduled away from what they were supposed to be doing at that point to return to the newly-arrive material.

One approach for trying to address this problem is reductionist in nature: for each disruption event, create an estimate of the delay caused by that one disruption. In the case of rework, how much time will it take to perform that rework. Or in the case of stolen material, how long will it take to source a replacement and have it delivered. Then, the time-impact of each individual event on the critical path can be assessed, enabling the quantification of the total time impact of all the events on the project duration.

This thinking is behind the approach suggested by the SCL, which recommends constructing a "Baseline", "Impacted", and "Accelerated" timeline for the project. The baseline is the plan, prior to any of the disruptions. The impacted timeline is calculated according to the critical path and reflects the total impact of all the individual events. And the accelerated timeline is what the contractor is capable of achieving (or has in practice achieved) if they work hard and bring on additional resources.

But a reductionist approach is flawed in this scenario, since it assumes that the individual disruptions and delays are sufficiently independent events (especially if they are not on the critical path). In practice, any construction project is a tightly coupled network, invalidating that assumption. A piecemeal approach to time delays doesn't necessarily reflect the system-wide impact of the total sum of the disruptions; in this case the whole is different than the sum of its parts. Even the necessity of starting tasks, then stopping when disruptions arise, then starting again can have costs, as fragmented work carries the cost of task switching.

A New Metric

To that end, a new metric was developed, that incorporates the Flow and Value approaches that are distinct from a pure-Transformation approach. The metric is based on an analysis of the level of Work in Progress (WIP) over the lifetime of the project.

As Little's Law (Hopp and Spearman 2011) describes, WIP is directly related to production throughput and the cycle time of products leaving the system. WIP has long been a focus of Lean thinkers, as WIP is inventory, which is a form of waste (Ohno 1988). Early pilgrims to Toyota factories described what we now call Lean as "Just in Time" production, as their attention was drawn to the low levels of WIP in the production system. In the world of software, the "Kanban" approach seeks to limit the WIP of work tasks, under the understanding that this will inherently improve the throughput of individual tasks.

In construction, particularly linear infrastructure projects, the concept of how to measure WIP is a bit more amorphous and up to the discretion of a planner. A unit of work might be a sub-area of a building, or a room, or in the case of a new road, a "roadel"(Haronian and Sacks 2020). The important aspect is not finding a globally accepted definition of what the "unit" is as much as being mindful of what is appropriate for the project in question and then studiously tracking the level of WIP throughout the lifetime of the project.

In the case study project, WIP was defined as sections of the train tracks of roughly equal length. Due to the differences in the nature of the different tasks, the WIP was defined differently for each.

The graphs in Figure 5 show the levels of WIP of the tasks over the lifetime of the project, both Planned and Actual. The WIP is the amount of "open" work areas, either according to the original plan or those that the contractor had to leave “open” due to the ongoing disruption events. The disruptions prevented the contractor from completing the works as planned and closing out work areas, leaving the WIP high. Trades were often forced to move the work teams among the various areas to address the problems as they appeared. Keeping many work areas open at the same time (high WIP levels) increased costs due to excess transportation of materials, equipment and tools, costs of damages, repair costs, and so on. In other words, WIP is both a waste and it leads to the other wastes, an insight as old as Lean itself.

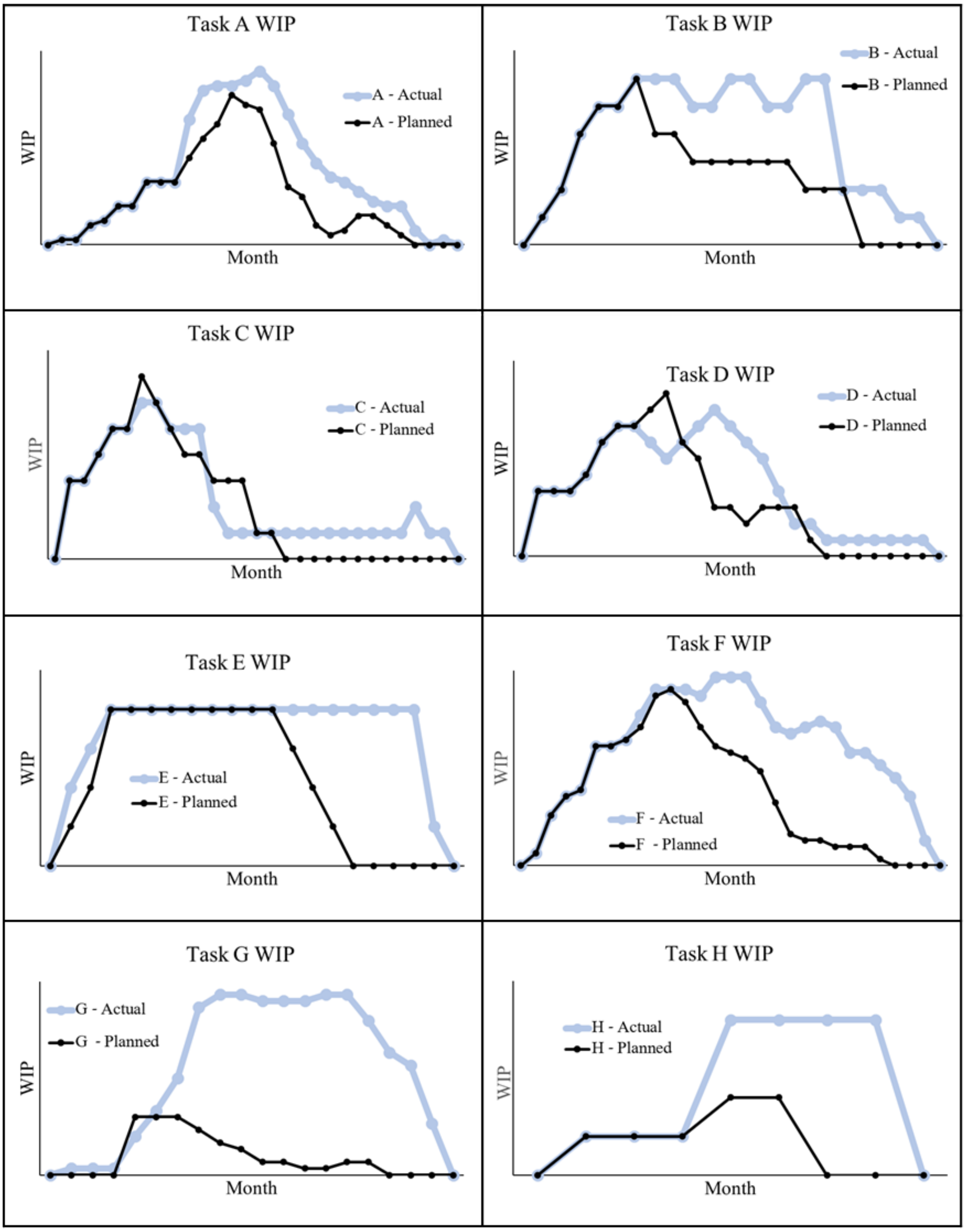

Figure 5: Planned versus Actual WIP for Each of the Tasks, over the Course of the Project

The proposed new metric integrates the WIP curve over the lifetime of the project, and compares the planned versus actual. In other words, the area under each of the curves, which has units of "WIP * time." For each time interval, the open WIP is summed, for both the plan and the actual. This metric is useful because it provides a concrete, flow-based measure of how the disruptions to the flow are leading to work areas that can't be close out and which continue to "gather" wastes. The metric is easy to compute (in this case, merely counting the number of open units each month) but also connects directly to the overall efficiency and effectiveness of the production system, in light of the disruptions.

RESULTS

For the case study, the new metric (WIP-Time) is shown in Table 2.

In this project, the WIP (and in turn the metric) was broken down by task, instead of looking at the WIP for the entire project all together. The reason this was done was in order to increase the fidelity of the measure. The WIP for the entire project jumps quickly to 100% and then stays there until the end of the project timeline, which means that the WIP-Time metric at the level of the project devolves into a proxy for the project timeline (both planned and actual). The project timeline, which a useful outcome measure, is less focused on the quality of the Flow. As the main goal of the proposed metric seeks to measure, in order to derive use from this indicator, it was computed at the task level.

Table 2: WIP-Time metric for each of the project tasks

Task	Planned WIP-Time (Unit-Months)	Actual WIP-Time (Unit-Months)	% Overrun
A	289	425	47%
B	55	87	58%
C	57	66	16%
D	90	113	26%
E	45	70	56%
F	318	533	68%
G	53	321	506%
H	7	19	171%

As can be seen, the WIP-Time overrun ranges from a modest 16% up to 506%. The latter was for Task G, which included laying the communication systems infrastructure for the trains. This was very precise and sensitive work, which was particularly vulnerable to interference and damage, as the disrupters soon learned. This was part of the reason that the WIP was planned to be so low, but in practice, the workers found it difficult to close out the work areas for this task.

In this case study, the metric has been deployed at project completion, as part of the efforts to quantify the scope of the disruptions that caused financial damage to the contractor. But it could also be deployed as a "live" metric, where the numbers are updated weekly or monthly throughout the project lifespan, to draw attention to the problem areas of the project where flow is currently suffering the worst.

CONCLUSIONS

This work presents a preliminary analysis for the impact of disruptions on production flow in construction projects. The proposed analysis and "WIP-Time" metric, as demonstrated on the case study, enables the evaluation of the impact of disruption events on production flow, as reflected by basic production parameters, for each type of activity and trade. The new metric has the advantage of simplicity of calculation while simultaneously connecting directly to the quality of the project value creation. The findings align with what was reported by the construction team on site, indicating that the disruptions prevented the completion of tasks and location handovers, forcing redundant movement, and making the work plans unreliable. The analysis presented in this paper is contrary to the traditional evaluation methods that view production exclusively through a "transformation" lens, without addressing aspects of production flow. The findings provide motivation for further work required to formulate a systematic methodology for evaluating the impact of disturbances on the production flow.

While this project was unique in the political landscape that it was developed and deployed in, there are other scenarios where there may be a number of disruptions, such as other parts of the world with political instability. But any project has disruptions and delays, even if not so many or from inimical third parties, and a proper measure of Flow can serve them, as well.

A large limitation of the work is the open question about the accuracy of the plan. Since the plan is the basis for comparison with the actual outcome of the project, if it is incorrect, then the metric in turn may be equally divorced from reality. Yet in the case of linear infrastructure projects, which tend to have more benchmarks and fewer engineering "surprises", it is possible that the planning is more accurate. Also, a flow metric such as this one does not apportion "blame" in the sense that the metric itself is agnostic as to the cause of the poor flow, be they external disturbances (as in this case study) or internal mismanagement or poor decision making.

Future work is required to turn this general metric into one that can be more directly translatable into financial terms, since as described above, it can be hard to put a monetary figure on poor flow. Likewise, it would be beneficial if the impact of external disruption events could be teased out from those of internal problems (i.e. inefficiencies that are due to or the fault of the project management/execution). And while this case study was a retrospective, the proposed metric could be deployed as a "live" measure of project performance in an ongoing project, with the impacts of its implementation being studied.

Another tack is to examine how worker morale due to a large number of disruptions can impact the project flow, as this project definitely struggled with a demoralizing effect in the face of repeated and ongoing interferences to the work, which took a toll on the workforce.

Ultimately, a Flow-based approach to measuring projects will have benefits, as the metric will in turn bring the focus of project management to the impact on the flow of the evolving nature of the project.

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PROCUREMENT OF COLLABORATIVE PROJECT TEAMS – A LITERATURE STUDY

Trond Bølviken[1], Una Obiose Kriston Nwajei[2], and Magnus Mikael Hellström[3]

ABSTRACT

In construction the procurement phase is the connection between the definition phase and execution. Thereby it establishes crucial preconditions for success (or failure) in execution by establishing a shift from competition to collaboration as the fundamental logic in the relationship between customer and supplier. The paradox of the procurement of projects in general and collaborative projects in particular is its aim of establishing collaboration through means of competition.

The paper presents a literature study of methods used in the client's procurement of teams in collaborative project delivery models such as Integrated Project Delivery (IPD), Alliancing and others. Five procurement methods are identified: Direct Negotiations (DN), Team-Based Procurement (TBP), dual Target Outturn Cost (dTUC), Competitive Dialogue (CD) and Best Value Procurement (BVP). Three methods for comparing alternatives are also identified: Weight Rating Calculating (WRC), Best Value Selection (BVS) and Choosing by Advantage (CBA).

The paper discusses public procurement, procuring the team in one or several steps, early or late setting of targets related to Target Value Design (TVD), the use of qualitative and quantitative evaluation, the need to adjust the procurement method, and the need for information and training. The possibility of procurement based on design solution is also presented.

KEYWORDS

Alliancing, Collaborative contracts, Integrated Project Delivery, Procurement, Relational.

INTRODUCTION

Construction is a commercial activity (business) and, as such consists of customers (buyers) and suppliers (sellers). A construction project consists of chains of customers and suppliers where most suppliers also have sub-suppliers for whom they are customers and side-suppliers for whom they are not. In the relationship between customer and supplier, the customer is the principal, defining if, what, how, and when to buy; in contrast, the supplier is an agent supplying something (information, a production process, or a physical thing) to the principal and acting on the order and behalf of the principal (Eisenhardt, 1989). In the construction industry, the customer, initiating and buying the entire project is often referred to as the client, while the parties using the constructed object (the clients of the client) are often referred to as end-users.

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The relationship between customer/buyer/principal and supplier/seller/agent undergoes three generic phases. In the first initial phase, often referred to as the definition phase, the customer defines if, what, how, and when to buy. He/she acts on their own behalf and has not entered a commercial relationship with the supplier, who holds no formal or binding position (although he/she might of course try to promote himself to the customer). The second phase establishes the formal and binding relationship between the customer and the supplier. The customer decides from whom he/she will procure, and the commercial terms are agreed between the parties. Taking the customer's perspective, we will refer to this as the procurement[4] phase. In the third phase, execution, the delivery takes place.

By passing on the need and intents of the customer to the supplier, the procurement phase is the connection between the definition phase and execution. Thereby it establishes crucial preconditions for success (or failure) in execution. It also establishes a fundamental shift from competition to collaboration as the fundamental logic in the relationship. By competition, we mean that the customer, in one form or another uses the presence of competing suppliers to gain an advantage for himself, while the suppliers try to exploit their strengths. Procurement occurs in a market where the parties look after their own commercial interests. This is done through different forms of direct and indirect competition. By direct competition, we refer to competitive tendering and parallel negotiations, and by indirect competition, we refer to the option for the customer to terminate exclusive negotiations and contact an alternative supplier. Through the procurement phase, the competitive relationship between the customer and several potential suppliers is replaced with an exclusive relationship between the client and the one chosen supplier for the execution phase. This makes collaboration between the two a fundamental requirement in the relationship within the execution phase (even though there will also be conflicting issues and a need for control)[5].

It is, however, commonly agreed that the levels of conflict are often too high and value creation too low in construction. Both public and private clients have traditionally, to a large degree, used transactional contracts awarded by low-bid tendering, taking only price into consideration. These traditional project delivery models have been seen as a major obstacle to improvement and have resulted in an increasing interest in the development of new collaborative project delivery models, such as Integrated Project Delivery (IPD). They are all based on relational contracting (Nwajei, 2021)[6] and aim at high levels of collaboration and the elimination or reduction of the principal-agent problem (Nwajei et al., 2022).

The reasoning above leads us to the formulation of the fundamental paradox of the procurement of projects in general and collaborative projects in particular: it aims at establishing collaboration through means of competition. A good start is often crucial for the success of a project, as in the expression “well begun is half done”. This is the reason why, according to Klakegg et al. (2021), procurement is one of the key elements that constitute a

[4] In their book *Collaborative Project Procurement Arrangements* Walker & Lloyd-Walker (2015) use the term procurement in a different way, referring to Project Procurement Arrangements and Relationship-Based Procurement (RBP), what we would call Project Delivery Models and Collaborative Project Delivery Models (Nwajei et al. 2022). In this paper we see the procurement process as consisting of three phases: 1. the design of the process. 2. the procurement process, (identifying and comparing alternatives and their differentiating features), leading up to 3. the actual procurement (the decision of whom to engage and the closing of the agreement which the chosen party). Our paper is related to phases 1 & 2 as the specific phase by which the relationship between the client and his supplier(s) is established.

[5] This balance and the fact that the parties must pursue both the interests of the other party and the interests of their own, is called the principal-agent problem and is the topic of agency theory (Eisenhardt, K. M. (1989). Agency theory: An assessment and review. *Academy of Management review, 14*(1), 57-74.

[6] In literature and different parts of the world, variants of these models are named Integrated Project Delivery (IPD), Partnering, Alliancing, Lean Project Delivery, Collaborative Contracting, Relational Contracting, and probably others. The differences between these variants are not the topic of this paper, and we will for ease refer to them all as IPD.

project delivery model. Lahdenperä (2012) describes a need to balance between early collaboration and competitive tension. One of the key issues in agency theory is the risk of adverse selection of a supplier (agent) (Eisenhardt, 1989).We could therefore expect the new collaborative project delivery models to have a high emphasis on how to approach procurement, that is, how to carry out the competitive selection of the team in a way that, instead of hindering, facilitates collaboration in the execution phase. This turns out not always to be the case. Research has to a large degree, focused on the collaborative processes in the execution phase, typically through observation of case projects. Nwajei (2021) points out that gaps exist from the limited empirical evidence on this subject and suggests further empirical examination of procurement and its effect on the relationship between the parties. Nwajei et al. (2022) summarise how the central components of collaborative project delivery models are described in literature and find that the selection and formation of the team is addressed as one of the fundamental functions of IPD in only two out of eight referred articles.

This lack of attention leaves researchers with limited overview of the procurement methods used and hardly any knowledge of the consequences of the different procurement methods both for the procurement and subsequent development and execution phases. This paper is part of a Ph.D. research project addressing these questions through understanding how IPD projects are, could, and should be procured. The paper presents the results of the first step: a study of how procurement is described in existing IPD-related literature. First, we describe the method used in the study. Then we present and discuss the identified procurement methods related to IPD. The goal is primarily to identify and give an overview of the methods, not to discuss their pros and cons.[7] The second step will be to expand and include empirical data in a journal article that will address the paradox of IPD procurement.

METHOD

The paper presents the results of a systematic literature review, of the procurement of a team in IPD contracting in construction. The review is based on Booth et al. (2016) guide to conducting a systematic and rigorous process and is in accordance with PRISMA reporting standards.

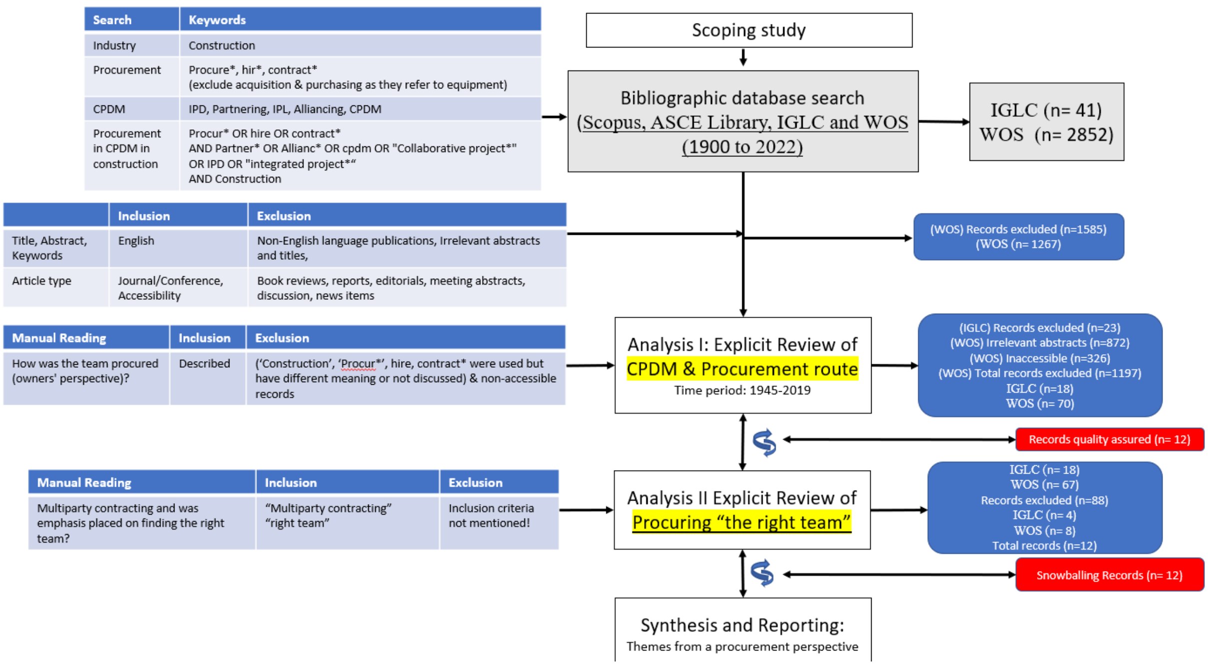

Figure 1: Flow chart of the literature search

[7] Walker & Lloyd-Walker (2015) discuss pros and cons regarding some of the procurement methods we identify in this paper.

This search, see Figure 1, followed the following steps: 1. A systematic search in scientific databases, and 2. Snowballing from identified articles in combination with direct mail to some of the main contributors to the IPD literature asking about the literature on procurement of IPD they may be acquainted with.

SELECTING JOURNALS AND PAPERS

The review involved searching for 'peer-reviewed journals' in the World of Science database (WOS) and the International Group for Lean Construction database (IGLC) from 1900 to June 2022. A total of 2852 articles from WOS and 41 articles from IGLC were identified that had abstracts, title and keywords containing: 'Construction' in combination with: 'Procure*' OR, 'hir*' OR 'contract*' OR 'IPD' OR 'Partnering' OR 'IPL', 'Alliancing' OR 'CPDM' as shown in the flow chart, Figure. 1.

The search results were cleaned, excluding false positives (literature on a different or unrelated topic), non-English language publications, book reviews, reports, editorials, meeting abstracts, discussions, and news items, (WOS = 1585, IGLC = 0). Second stage cleaning, checking the title, abstract, keywords, and, if necessary, the full publication, identified irrelevant abstracts (WOS = 872, IGLC = 23) and inaccessible articles (WOS = 326, IGLC = 0). Articles were rejected if one of the words 'procure', 'hire' or 'contract' was used in a different meaning or not discussed.

Third-stage cleaning validated the efficacy of the exclusion criteria by double-checking the results resulting in 12 new admissions to WOS articles. Further cleaning reduced 100 articles to 85 articles (67 WOS and 18 IGLC), by examining the significance of the articles in discussing 'procuring the right team'.[8] Subsequently, this number (85) was further reduced to 24 articles by only retaining articles relevant to multiparty contracting (IPD, alliancing, consortium or multiparty contracting').

In line with the approach taken by Booth et al. (2016), the quality of the articles was appraised. Therefore, articles and publications not included as part of the search were instead used as a starting point for additional citation searches (snowballing). In total, we ended up using a total of 24 documents (articles, handbooks/guides and books), of which 8 came from the WOS search, 4 from the IGLC search and 12 were snowballed documents.

PATTERN OF PUBLICATIONS

Compared to the total amount of publications on IPD, the number of publications addressing IPD procurement is limited, figure 2. Guide/handbooks and were the most useful sources of information figure 3. The publications on IPD procurement typically describe one or more procurement methods; some also give advice. However, only very few discuss the consequences of the different procurement methods for the procurement process itself. More important than the effect on the procurement process is the effect on the subsequent development and execution phases, and as a result, for project success and outcome. We have, in our search, found no publications discussing this and no publication giving an overview similar to the one we present in this paper.

[8] After the search, we analysed the papers categorically into descriptive (describing how IPD teams are procured) and prescriptive (giving advice and describing how IPD teams should or could be procured). This turned out to be unsatisfactory, the reason being that some papers contained a mix of the two, while in other cases it was somewhat unclear to what degree the presentation actually was descriptive or prescriptive. We have, therefore, not included the coding in the presentation of the search.

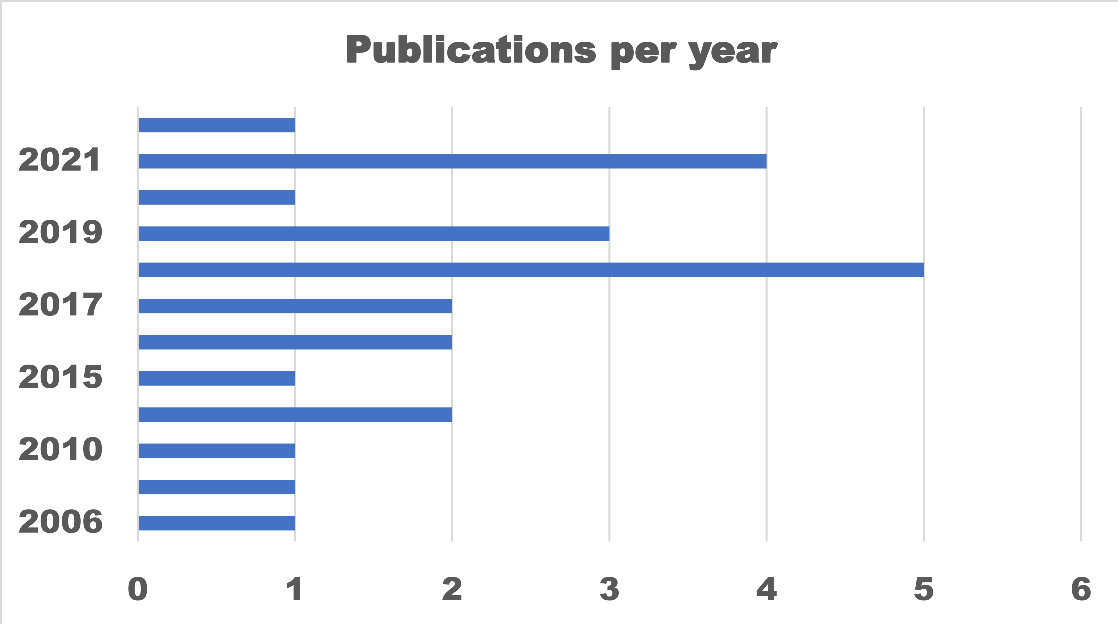

Figure 2: Number of publications per year from the identified literature

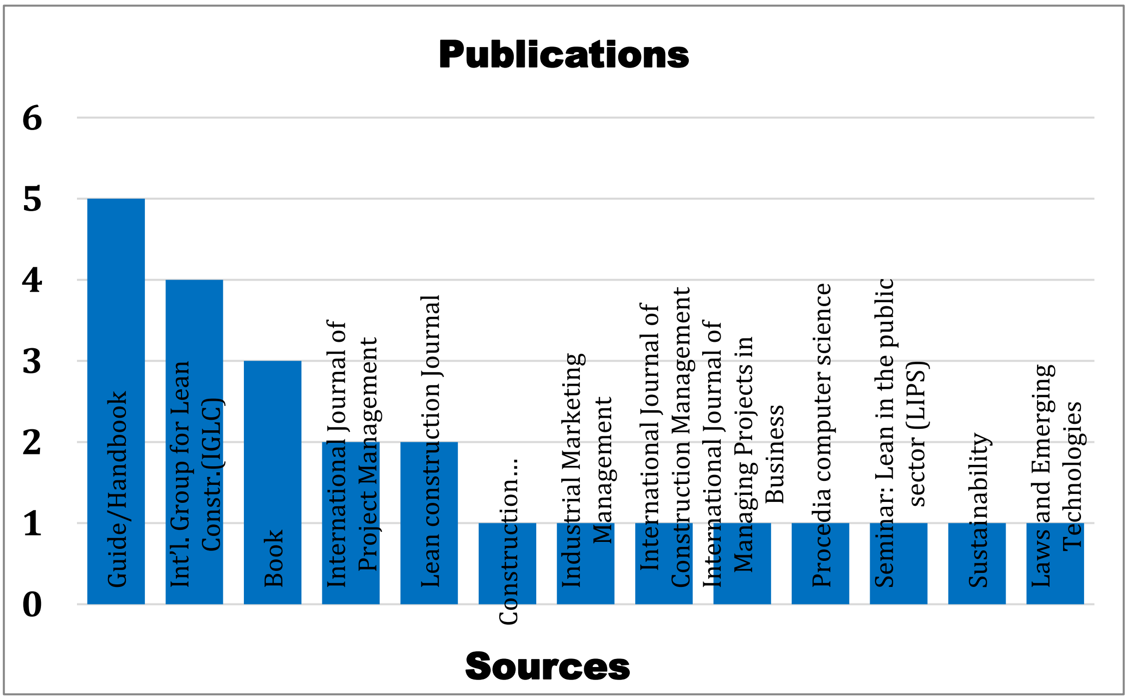

Figure 3: Number of reference sources from the identified publications

PROCUREMENT METHODS

In general, a project proposal might address the following components: solution, process, team, price, and commercial arrangements (Department-of-infrastructure-and-regional-development, 2015). Several authors emphasise that collaborative project delivery models like IPD cannot be based on price alone and require a procurement process based on competence, qualifications, and (product and process) value (e.g. (Heidemann & Gehbauer, 2010; Lahdenperä, 2012; Mesa et al., 2019; Schöttle et al., 2015). According to the Department-of-infrastructure-and-regional-development (2015), a selection process that optimises the opportunity for innovation and differentiation between the proponents should result in better Value for Money (VfM) for the client.

All procurement methods identified in our literature search evaluate the team using techniques like interviews and workshops. In addition to the team, price, or value (related to product or process) other factors are taken into consideration in several of the methods. We have found no example of procurement methods related to IPD focusing only on price or value.

DIRECT NEGOTIATIONS

Some clients might have established relations with design and construction companies they prefer to work with. Crespin-Mazet et al. (2015) refer to this as “relational congruence in the project network”. When this is the case, the client might, instead of evaluating several companies, simply choose to enter into direct negotiations with their preferred partner (Allison et al., 2018; Crespin-Mazet et al., 2015).

TEAM-BASED PROCUREMENT

Several authors (e.g. (Allison et al., 2018; Department-of-infrastructure-and-regional-development, 2015; Fischer et al., 2017; Frydlinger et al., 2016; Mesa et al., 2016, 2019) describe what we in this paper call Team-Based Procurement (TBP) approaches. In the first phase, two or more teams are evaluated, leading to selection of a preferred team. In these approaches, only the team is evaluated, looking at factors like qualifications, competence, previous experience, cultural congruence, alignment with the client’s goals and ambitions, and relational and collaboration skills. Prices or product characteristics are not factors.[9] After selection, the preferred team works with the client to develop the product, the corresponding target price, and other commercial conditions. If this succeeds, the IPD agreement is signed. If not, the client must try all over again with another team (Fischer et al., 2017).

The single Target Outturn Cost (sTOC) process is an Australian variant of Team-Based Procurement. In sTOC there is a pre-qualification process before two or three contenders are qualified to undertake a selection workshop in which they present and discuss their proposed team and ideas for design solutions. They may also, in some cases, be required to offer a fee structure, expanding the parameters beyond the evaluation of the team. (Department-of-Treasury-and-Finance, 2006; Ross, 2009; Walker & Lloyd-Walker, 2015; Walker & Lloyd-Walker, 2020).

DUAL TARGET OUTTURN COST PROCESS

The dual (also referred to as multiple) Target Outturn Cost (dTUC) process is a variant of the single process described above (Department-of-Treasury-and-Finance, 2006; Ross, 2009; Walker & Lloyd-Walker, 2015; Walker & Lloyd-Walker, 2020). The difference is that the competitive elements (regarding team, price, and value) have more emphasis in the dual process. The client workshops in parallel with two preferred teams, and both teams calculate a target price. Both team, price, and value are evaluated in the final selection of one of the two competitors. The goal is to select the best-priced solution with the most attractive team skills package (Walker & Lloyd-Walker, 2015).[10]

COMPETITIVE DIALOGUE

As Competitive Dialogue (CD) is presented by Fernandes et al. (2018), the procurement process is divided into two phases, the contract notice phase and the tendering phase. In the contract

[9] The Department of Infrastructure and Regional Development (2015) therefore calls this procurement approach “Non-price selection”.

[10] The Department of Infrastructure and Regional Development (2015) calls this Full Price Selection. If only fees and not total costs are evaluated, they use the term Partial Price Selection. They do however warn against the latter. Mesa et al. (2016) use the terms Best-value total and Best-value fee

notice phase, the client prepares the request. Based on this, the suppliers submit a request to participate in the competition. The client then selects a limited number (approx. 3) of tenderers through a prequalification process. In the tendering phase, the client has individual parallel rounds of negotiations with all tenderers. During the negotiations, product, process, and commercial-related issues are discussed before the client makes an updated and final call for proposals, and the tenderers prepare and submit their final tenders. Finally, the client evaluates the tenders and awards the contract.

Hietajärvi et al. (2017) present a variant of dTUC and CD (without naming it so). In the first phase, the client prepares the tendering document, which includes goals, budget estimates, and evaluation criteria. Based on this, competing consortiums are established and prepare to present a first tender. The client then selects 3-5 consortiums to continue to the next phase, the negotiation phase. In the negotiation phase, the client and each consortium have workshops where they work collectively to develop content for the proposed project. Based on these workshops, the client evaluates each consortium and selects two to continue the process. These two then update their tenders, including price. Finally, based on the updated tenders and workshop experience, the client selects the winning consortium, with whom they sign a contract for the next phase - development.

Also, Jobidon et al. (2021) present a procurement method that seems to be a variant of dTUC and CD. This method is used in Canada.

BEST VALUE PROCUREMENT

Best Value Procurement (BVP) is founded on the understanding of the supplier (the contractor) as an expert and allows the client to be a non-expert (within the profession of the supplier). The idea is early contractor involvement (ECI) in value creation and risk reduction from the client's perspective in combination with an effective procurement process. The process is divided into four phases: preparation, selection, clarification, and execution. In the preparation phase, the client makes a core document describing project objective and scope, the selection criteria and their weighting, and a maximum price (budget ceiling). Pre-qualification is recommended. In the selection phase, each competing supplier prepares a tender consisting of three two-page documents, in total six pages: in the Level of Expertise document, the supplier describes and documents their capability to fulfil the client’s requirements; in the Risk Assessment document they identify the most important risks from a client perspective and a risk mitigation plan, in the Value-Added document the vendor presents recommendations that can increase value for the client. Based on the three documents, price, and interviews with core members of the vendor’s project leadership team, the client selects a preferred vendor. In the clarification phase, the preferred vendor prepares and presents technical documentation, a project schedule, and key performance indicators. Finally, the contract is negotiated and, if the parties agree, signed. In the execution phase, the risk management plan and periodic risk reports are dynamic documents (Narmo et al., 2018).

BVP has been used in the procurement phase for a IPD road construction project in Norway (Johansen et al., 2021). Wondimu et al. (2018) compare CD to BVP, but not in relation to their applicability in IPD project.

METHODS FOR COMPARING ALTERNATIVES

While the procurement methods describe the entire procurement process, the methods for comparing alternatives focus only on the part of the process (how to compare the alternatives). This means that a method for comparing alternatives will be part of a procurement process and that a procurement process might use different methods for comparing alternatives from case to case. Schöttle et al. (2015) describe and compare three methods (for comparing alternatives-in our case, tenders. They compare the three methods through simulation in a constructed case (based on a real turn-key project). The simulation demonstrates that the size of the differences in scores and the tenders' ranking depends upon the method used.

WEIGHTING RATING CALCULATING

Weight Rating Calculating (WRC) is also referred to as Weighted Sum, Scoring System, Ranked Scoring or Utility Analysis. In WRC, the bid price is one of several factors. The weighting of factors and attributes is done directly and indicates the importance of each factor for the client.

BEST VALUE SELECTION

Best Value Selection (BVS) is also referred to as Best Value Scoring Analysis. BVS is based on WPC but differs in the evaluation of the bid price. In BVS, all factors apart from price are calculated as a value/qualification score. The bid price is then divided by the value/qualification score. The smaller this ratio is, the better is the proposal (high value-for-money).

CHOOSING BY ADVANTAGE

In Choosing by Advantage (CBA), the advantages of the alternatives are compared to decide their importance. What is important in CBA is to identify which factors will reveal significant differences between the alternatives, not what factor (in the abstract) will be important in the decision.

DISCUSSION

Through our literature review, we have identified seven unsettled issues, unexplored solutions, and recommendations to team selection in collaborative projects. These are discussed below.

PUBLIC PROCUREMENT

When procuring, public clients are bound by regulations, motivated by considerations of anti-corruption, fair competition, and effective use of public money (value-for-money). They demand the use of objective criteria defined before tendering starts and to be able to document the procurement process. This requires a stable framework and limits the client's ability to adjust during the process. Otherwise, bidders can make claims, complicating the process, forcing the client to pay compensation, or even nullifying the results (Schöttle et al., 2015). The different considerations might pull in different directions, e.g., fairness might interfere with value-creation in the procurement process (Jobidon et al., 2021). Private clients are in a different formal position, with few or no constraints on formal competitive procurement (Lahdenperä, 2012).

It is claimed that a shift to new procurement and project delivery models will require a change in public regulations (Cohen 2010, (Cohen, 2010; Ghassemi & Becerik-Gerber, 2011; Heidemann & Gehbauer, 2010; Rodrigues & Lindhard, 2021), but this is obviously not always the case, and the situation differs between countries: the mood and interpretation of the regulations is gradually changing (Walker & Lloyd-Walker, 2015) and we have in many countries seen new models being promoted and used by public clients also within the framework of existing regulations. In Australia, Alliancing and related procurement processes are well established in public projects. (Department-of-infrastructure-and-regional-development, 2015; Walker & Lloyd-Walker, 2015).

According to Jobidon et al. (2021) dysfunctional regulations and the absence of clear directives and guidelines regarding collaborative models create "a normative fog" (p. 5) that causes uncertainty and complexifies the pathway for public clients as well as tenderers.

Schöttle et al. (2015), discuss the different methods for comparing alternatives that have specific potential challenges when it comes to compliance with public procurement regulations.

PROCUREMENT IN ONE STEP OR THROUGH A SUCCESSIVE TEAM EXPANSION?

Fischer et al. (2017) argue that instead of procuring the entire IPD team in one step, one should start out with a small team and expand it with new participants along the way. This view is supported by Rodrigues and Lindhard (2021). According to the Department-of-infrastructure-and-regional-development (2015) the decision of one or successive [11] steps should be considered from case to case. Both Crespin-Mazet et al. (2015) and Mesa et al. (2019) describe two cases, one where the entire core group was selected at the same time and one case where the parties were selected in two or three steps. Successive selection of new partners could in principle be done using any of the methods described above.

As for the IPD contract, a successive team expansion can be handled in two alternative ways, a sub-agreement approach where the new parties enter a separate agreement linked to the existing agreement, and a joining agreement approach where the new parties join the existing agreement (Fischer et al., 2017).

SHOULD TARGET PRICE BE SET BEFORE, DURING OR AFTER THE PROCUREMENT PROCESS?

Target Value Design (TVD) is a concept related to IPD. In TVD, the target price is set early (before the start of the design process) and used as a constraint to maximise customer value (Ballard, 2011). The alternative to this approach is to set a target price during or after design. In the first case, the target is set solely by the client; in the two latter cases, in dialogue and negotiation between the client and the team of designers and contractors. The procurement methods described above have different approaches to this. In Best Value Procurement (BVP), the target is set by the client as a precondition that the tenderers must accept if they want to participate in the competition. In dual Target Outturn Cost (dTUC) and Competitive Dialogue (CD) the target is set as part of the procurement process, while in Team-Based Procurement (TBC) it is set after the team is selected.

Johansen et al. (2021) discuss early versus late setting of the target price. They argue that if the target is set early, it must be adjusted during or after procurement. This leads them to recommend that the client should set an allowable price early, but that the target price is set in dialogue with the chosen team during or after procurement. References to an Australian debate on a single versus a dual Target Outturn Cost process can be found in Ross (2009).

SHOULD PROCUREMENT BE BASED ON QUALITATIVE OR QUANTITATIVE EVALUATION?

Apart from some possible variants of Competitive Dialogue (CD), all identified procurement methods have a high degree of qualitative evaluation. Such qualitative evaluation cases can be transformed to a quantitative expression through one of the methods for comparing alternatives presented above, or they can be handled purely qualitatively. From the procurement methods identified, the decision to enter Direct Negotiations (DN), will normally be taken based on a purely qualitative judgement. In contrast, dual Target Outturn Cost (dTUC) and Best Value Procurement (BVP) use a quantifying method. Team-Based Procurement (TBC) might use both approaches.

COULD PROCUREMENT BASED ON DESIGN BE AN ALTERNATIVE?

In traditional design competitions, the client evaluates design proposals (mainly qualitatively), and the preferred proposal is selected to be further developed together with the client. In design and price competitions, alliances of designers and contractors present design proposals with a

[11] The Department of Infrastructure and Regional Development (2015) uses the term "progressive".

lump sum price. In this case, the client makes a (qualitative and quantitative) evaluation of the proposals and selects the best value-for-money alternative.

We have in literature found no example of design-based procurement related to IPD. Could this be an alternative in some cases?

THE NEED TO ADJUST THE PROCUREMENT METHOD

In a procurement strategy for an IPD project, the client must answer several questions: What is of importance (value) for us as a client? What is to be evaluated in the procurement process, teams, product proposals, process proposals, prices and/or commercial arrangements? Should the entire team be procured at once, or should we use a successive approach? Should there be competition between teams/companies, or should we negotiate directly with one preferred partner? Should the evaluation be based on qualitative and/or quantitative parameters? How should the parameters be compared and weighted? For example, if we are going to evaluate prices, should this be fees, unit prices and/or aggregated prices for parts of or the entire object? Should aggregated prices be targets or maximums?

The combined answers to these questions create a potential number of procurement methods far beyond the limited number identified in this literature review. According to Department-of-infrastructure-and-regional-development (2015); Lahdenperä (2012); Walker and Lloyd-Walker (2015), the procurement method must therefore be adjusted and specified in each project. This is a situation different from procurement of unit-price or lump-sum contracts in open hard bidding. Here identical strategies and methods might be used from project to project. Especially in public projects, this makes the procurement process more challenging. In addition, it increases the risk of alleged or actual breach of rules and, consequently, potential complaints.

THE NEED FOR INFORMATION AND TRAINING

Selection criteria should be practical and easy to understand in an unambiguous way by both clients and tenders. New procurement methods are unfamiliar to people, more complicated, and harder to grasp than traditional price-only procurement. We must also expect the procurement method and IPD to be new to many participants. Several authors see training of both client and potential teams as important for success in the procurement process (e.g. (Hietajärvi et al., 2017; Narmo et al., 2018; Walker & Lloyd-Walker, 2015).

CONCLUSIONS, LIMITATIONS, AND FURTHER RESEARCH

We have in this paper presented the procurement methods related to IPD that we have identified through a systematic literature review. The goal has been to give an overview, not to go into detail regarding the different methods.

Some of the presented papers are purely descriptive, describing procurement methods used. Others are prescriptive, advising on how procurement of IPD teams should or should not be done. Others, again, are a mix of the two. A few contributions discuss consequences of the different procurement methods for the procurement process (Department of Infrastructure and Regional Development 2015, Walker & Lloyd-Walker 2015). The most important is the effect of the procurement method for the subsequent development and execution phases, and as a result, for project success and outcome. In the introduction, we formulated what could be called the paradox of IPD procurement: it aims at establishing collaboration through means of competition. In our literature search, we found no papers discussing this, neither theoretically nor empirically. This paper contributes to the core conceptual conversation and advancing insight on procurement of collaborative construction deliveries in order to push forth discussions and debates in neglected strands of the construction management and organization field.

IPD is often presented as a game-changer in construction. This is contrasted by its slow uptake. If IPD is a game changer, why is it not changing the game quicker? In IPD procurement, the procurement process is more complex and demanding for the client than in traditional price-focused procurement. At the same time, the client has limited security for what he will actually get when he enters the contract. Can this be part of the reason for the slow uptake of IPD? Based on this literature review, the plan is to address these questions in the next step in our research project on IPD.

There are two main limitations in the type of literature search used: the terms used in the search and the presence of the relevant literature in the databases used. To compensate for this, we have snowballed from identified papers and asked some of the main contributors to the IPD literature for relevant references. The snowballing and direct requests resulted in several relevant papers but didn't change any of the main findings. We see this as an indication of that the search method used has given us a relevant and representative overview of the literature.

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SAFETY CULTURE IN CONSTRUCTION INDUSTRY OF NEPAL

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ABSTRACT

Safety culture is a critical aspect of ensuring safe and productive construction sites. However, many studies in the field of construction that focus on safety culture overlook the unique attributes of construction environments. Current models for safety culture in construction fail to fully encompass the dynamic and diverse nature of construction sites where individuals with differing backgrounds, professions, and levels of experience collaborate to complete projects. These individuals not only come from different cultures and speak different languages, but they also have various psychological, behavioral, and knowledge traits that can affect their safety practices and behaviors. Moreover, different organizations have different settings and perceptions about the safety of their workers and workplace, which can further complicate the development of effective safety cultures in construction. Therefore, there is a clear need for research that focuses on developing more context-specific models for safety culture in construction that can account for these unique attributes and complexities (Hallowell et al., 2016; Hinze and Tracey, 2016; Lingard et al., 2018). The present study presents a framework that incorporates multiple facets of safety culture, including psychological factors, organizational factors, knowledge and awareness, behavioral factors, safe working conditions, safety-oriented climate, resilience, and unsafe behaviors. The proposed framework captures the relationship between these variables and the safety culture of the construction industry in Nepal. The results inferred from the analysis of the survey showed that among the eight variables included in the study (psychological dimension, organizational dimension, knowledge dimension, behavioral dimension, safe workplace, safety climate, resilience, and unsafe behavior), seven of them (excluding unsafe behavior) had a direct positive impact on safety culture in the construction industry of Nepal. In other words, these seven variables were found to be positively associated with the development of a strong safety culture in the construction industry of Nepal. On the other hand, unsafe behavior was found to have a negative impact on safety culture, implying that if workers engage in unsafe behavior, it can undermine the development of a positive safety culture in the workplace.

KEYWORDS

Safety practice, safety culture, construction.

INTRODUCTION

In Nepal, most construction firms adhere to conventional safety practices. However, due to the government's relatively weak occupational health and safety regulations, there is a lack of effective safety management procedures, which leads to numerous accidents every day. Large corporations that use a lot of human labor hire locals from the project site as workers, but they

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rarely or never provide them with any safety orientation. This highlights the need for a strong safety culture in the construction industry in Nepal. Freshly hired laborers are immediately put to work, where they are unaware of any potential risks related to the building environment. Furthermore, the lowest-qualified bidder frequently receives the contract, and as a result, businesses forego investing in training programs and other measures to improve the industry's safety culture (Adhikari and Pradhananga, 2018; Koirala and Wasti, 2019; Shakya et al., 2018).

The management of workers' health and safety is crucial since it improves any industry's profitability, performance, and production (Ranasinghe et al., 2020). Improving safety performance in construction enterprises requires a thorough grasp of the variables influencing hazard detection and risk perception (Pandit et al., 2019; Ranasinghe et al., 2020). Due to the very high rate of injuries and fatalities that commonly occur in construction fields, the construction industry has a code indicating that it is extremely risky or unsafe (Talmaki and Kamat, 2014; Ghasemi et al., 2015). When compared to the manufacturing-based industry, where the risk of injury is 2.5 times larger, the likelihood of death in the construction sector is 5 times higher (Khosravi et al., 2014). The small unit of fewer than 10 workers working outside the urban workforce border in Nepal is not benefited from OSHA's legislative effort. Koirala (2016) acknowledged that Nepal has not yet ratified the core OSHA principle of the International Labor Organization (ILO). According to Olsen (2009), Nepal has not yet ratified OSHA Convention No. 155 of the ILO. According to trends in occupational injuries related to construction in Nepal, the number of fatal events rose from 5 to 13 between 1995 and 2009. (Joshi et al., 2011; Koirala, 2016; Sanjel et al., 2016). According to reports from Hämäläinen et al. (2006) and Koirala (2016), the rate of fatalities was 10.5 in China, 11.5 in India, and 29.9 per 100,000 workers in Nepal.

There hasn't been much research or previous studies on improving safety performance in the Nepalese construction industry, and what little there is focused primarily on defining external factors that do so, ignoring internal factors and the fundamental relationship between the safety enhancement factors in construction firms (Gautam and Prasain, 2011; Sukamani and Wang, 2020). Construction companies in developing countries face difficulties that are more fundamental, intricate, and severe. These concerns arise in a developing country like Nepal due to the general socio-economic unrest, ongoing resource scarcity, and general inability to find solutions to pressing problems. The lack of effective safety management procedures is a significant problem in the construction industry in developing nations (Koirala, 2016; Sanjel et al., 2016). To focus on accomplishing the goals of improving safety performance, it is crucial to develop the frameworks that the organization should adhere to and manage its resources.

LITERATURE REVIEW

The consequences of inadequate safety measures can have a significant impact on employees, their families, local communities, and the employer (Arboleda and Abraham, 2004). By reducing the frequency of workplace accidents, injuries, incidents, and illnesses, occupational safety can enhance efficiency, competitiveness, production, and profitability (as shown by studies from Chan et al., 2008; Hon et al., 2012, 2014). Accurate documentation of these incidents helps raise awareness and promotes the sharing of important safety information within the organization (Ra and Merisalu, 2010; Hussi, 2005). Effective communication of this information is crucial for managing safety knowledge within the organization (Nuez and Villanueva, 2011). Furthermore, businesses have a greater potential to learn and adopt best practices from other organizations and industry experts in the realm of construction safety (Järvis and Tint, 2008).

Organizational culture is often viewed as a component of safety culture, shaped by attitudes and values specific to health and safety issues (Clarke, 1999). According to Williams et al. (2020), the values, beliefs, rituals, traditions, and practices shared among members of an organization make up the concept of "safety culture" (Kartikawati and Djunaidi, 2018). There have been many efforts to develop a theoretical model of safety culture, with the Layer models (Reason, 1997; Guldenmund, 2000) and Triad models being two of the most widely used (Geller, 1994; Cooper, 2000). The idea behind Layer models is that by understanding the content of organizational culture, it is possible to analyse and improve safety-related elements. However, Layer models are often criticized for lacking objective evaluation tools and failing to account for the dynamic nature of culture (Cooper, 2000; Choudhry et al., 2008). Triad models, on the other hand, focus on the connection between psychological, behavioural, and situational factors in safety management (Cooper, 2000; Geller, 1994). To address these criticisms, Geller (1994) proposed a comprehensive safety culture model that recognizes the dynamic and interrelated nature of individual, environment, and behaviour. Cooper (2000) also developed a reciprocal model of safety culture that consists of three parts: subjective situational characteristics, internal psychological factors (how people feel), and safety-related behaviours (what people do). The model proposed in this research, considers the impact of psychological, organizational, knowledge, and behavioural dimensions, as well as the resilience of the safety culture, the safety climate, and instances of unsafe behaviour.

An organization's atmosphere often includes a variety of individual assessments of the workplace (James & James, 1989). These evaluations include assessments or cognitive appraisals of numerous fundamental workplace elements or traits, such as participation, leadership, communication, and creativity. It is thought that the combination of these assessments can significantly shape the actions and expectations of employees within the organization (Schneider, 1975). The idea that organizations can be seen as having several distinct climates, such as the climate for customer service, the climate for safety, and so forth, stems from the premise that the safety climate is essentially an offshoot of organizational climate. Actions done to improve the overall climate of the organization should also improve the climate for safety to the extent that these general climate aspects shape the climate for safety. Evaluation of these broad climate aspects should, in the end, give designers of interventions a more solid foundation on which to build and more proof that managing safety is not fundamentally different from managing other essential organizational responsibilities.

Typically, acquiring knowledge and skills in the construction industry happens through "on-the-job learning," which is how manual workers improve their knowledge and abilities (Golden and Skibniewski 2009). Learning while working contains both social and individual components (Collin and Valleala 2005). The employee's personal effort in repeating tasks, which is influenced by task features like complexity and mechanization as well as employee professional profiles like talents and prior experience, represents the individual aspect (Srour et al. 2018). The interaction and sharing of knowledge among crew members, which is influenced by the schedule structure, employees' prior experience, crew demographics, and workers' attributes, is comparable to the social part of learning (Kiomjian et al. 2020). Knowledge must be properly defined to comprehend the dynamics of the social side of learning. Knowledge is the skill and know-how a person possesses that enables them to do specialized tasks more effectively (Bock et al. 2005). On construction sites, the informal character of the knowledge-sharing process makes it extremely reliant on the interpersonal interactions between the knowledge transmitter and receiver (Thomas et al. 1998). As a result, the knowledge sharer starts to consider the benefits of the exercise, such as applying knowledge to job performance while managing time and learning from mistakes, or even producing new information by working together to boost team productivity. The outcomes could be quicker payment, employment referrals from other employers, and networking. Nevertheless, it could appear that competition suffers when knowledge is shared. Supervisors must devise strategies to encourage staff members to communicate their tacit knowledge if they want to keep it alive. The process of information sharing among workers is anticipated to be influenced by several social and personal elements, considering the social component of on-the-job training and the pragmatic aspect of tacit and explicit knowledge (Sanboskani et al. 2020).

French and Geller (2012) contend that for a safety infrastructure to be effective, it must actively encourage employee engagement. People modify their attitudes and beliefs to match their behaviors when they decide to change their conduct. Changes in behavior and attitudes are mutually reliant; there is a spiraling, reciprocal interdependence between our outward behaviors and our feelings. This is how minor adjustments in conduct and attitude can finally result in full commitment and involvement from an individual. Therefore, researching the behavioral factor appears to hold promise for enhancing safety performance in an organizational setting. The conduct of employees is the focus of the behavior-based approach to safety. This mechanism can lower injury rates through altering behavior. The behavioral-based approach to safety is solely concentrated on the measurable, observable behaviors that are essential to safety in a specific facility (Burton, 2012). When safety behavior programs are correctly implemented, they result in large improvements in safe performance and significant drops in occupational injuries and illnesses in workplaces with problematic rates of unsafe performance (Cambridge Centre for Behavioral Studies, n.d.). Recognizing employee safety behavior is crucial to raising an organization's overall safety performance. It is possible to evaluate how safe habits might be rewarded by identifying the factors that influence workers' safety behavior.

For the construction sector, safety is essential. Government agencies, business leaders, and university researchers have worked hard to enhance safety performance during the past few decades. For instance, Ontario province passed the Building Trades Protection Legislation in 1911 to govern the safety of tradespeople working in building construction; the Construction Safety Act replaced this act in 1962. (Ontario Ministry of Labor, 2012). A multitude of studies have been conducted to examine the effect of safety culture on safety performance, driven by events such as the Chernobyl Disaster in 1986 (Cooper and Phillips, 2004; Coyle et al., 1995; Dedobbeleer and German, 1989; Glendon and Litherland, 2001; Isla Daz and Daz Cabrera, 1997; McCabe et al., 2008; Neal and Griffin, 2006; Niskanen, 1994; Pidgeon, 1991; Siu et al., 2004). Because of these activities, the proportion of deaths in the construction industry has drastically decreased. However, several nations or regions, like Ontario and the US, have recorded a safety plateau. Over the previous ten years, the fatality rates in the US and Ontario construction industries have been flat. The secret to getting above the plateau is figuring out what influences construction safety performance. One of the elements that may enhance safety performance is the safety atmosphere. People's collective attitudes about workplace safety have been used as a barometer for the existence of abstract safety culture (Zohar, 1980). Regarding the parameters of the safety climate, there is no consensus. In the research studies on the safety climate in the construction industry, attention has been given to the following factors: management commitment, safety rules and procedures, housekeeping and safety equipment, supervisor, and coworkers safety perception (Colley et al., 2013; Dedobbeleer and Béland, 1991; Fung et al., 2005; Mohamed, 2002; Siu et al., 2003). However, other factors that are equally important to safety performance, such as reporting (Fung et al., 2005) and readiness (Hon et al., 2014), are rarely measured. In the meanwhile, the availability of injury data has decreased, making it harder to anticipate safety performance. All of this has forced us to look for a fresh strategy.

The concept of resilience has demonstrated its capacity to enhance safety performance over time. According to Bruyelle et al. (2014), Ross et al. (2014), and Vogus and Sutcliffe (2007), it is regarded as a capacity for an optimistic response and healing capabilities to routine usage as well as maintaining a high level of safety during stress and disturbance. This capacity is essential for human and organizational capabilities and viability (Carmeli et al., 2013). It has been suggested as a fresh strategy for the following generation of safety advancement (Hollnagel, 2015). In high-risk systems with difficulties associated, such as (a) a high degree of interconnection between the system's components; (b) unpredictability and variability, the application of resilience is especially applicable (Costella et al., 2009). A building site requires resilience to create prevention tactics because it is a complex, dynamic, and unstable system (Costella et al., 2009). Managerial commitment, reporting culture, learning culture, anticipation, awareness, and flexibility are the resilience dimensions that are most frequently recognized (Woods and Wreathall, 2003).

Construction sector accidents are complicated occurrences that can involve both the independent and reciprocal impacts of risky activities and conditions. Workers' performance and vision in the workplace might be impacted by dangerous behaviors. However, the driving forces behind the dynamic personalities in the construction business might be more complicated, making it crucial to concentrate on these important driving forces that affect employees' behavior (Jiang et al., 2015). Psychosomatic stress (Siu et al., 2004), safety climate (Fang et al., 2015), danger perception (Bohm et al., 2010), employee engagement, administration commitment, adequate source portion, and collaboration are some of the major elements that have been linked to workers' risky behaviors (Abudayyeh et al., 2005). Early in the 1980s, the safety atmosphere emerged as one of the key subcategories of safety, emphasizing management over actual safety. According to (Zohar et al., 2015 and Cheng et al., 2011), employees' perceptions of safety influence how they behave at work. The relationship between safety policies, procedures, and practices is emphasized by people's perceptions. Other studies have examined key factors that contribute to a safe work environment, such as safety perception, working conditions, safety programs, and management systems, and researchers have tried to identify dimensions of safety climate (Cheng et al., 2011).

METHODOLOGY

A survey was conducted to collect the perceptions of 44 construction practitioners and site personnel regarding the suggested variables. In addition to that, demographic factors like age, experience, profession, and gender were collected and inferences of these factors on other variables were computed and observed. This research is a descriptive study and inferential analysis is done to obtain the results of the research. This research is based on a survey of 44 respondents which is done through a questionnaire. Likert scale questionnaires were used to collect responses from construction practitioners and site personnel who participated in the survey. The Likert scale used a 5-point scale, with 1 indicating "strongly disagree" and 5 indicating "strongly agree" about their perceptions on various constructs developed in the theoretical framework as indicated in figure 1. The data collected was analyzed using SPSS software and MS- Excel. The interpretation is done by descriptive statics, ANOVA, Chi-Square, correlation, and regression tests.

To improve the research's validity and dependability, the researcher indulged himself to facilitate the respondents so that the response rate could be maximized, and probable errors could be minimized. Both the independent and dependent variables were separately tested using Cronbach’s alpha test of reliability to make certain that all designed questions are reliable. A validity construct of variables used in this study was analysed based on different scholarly articles and literature and is presented in table 1.

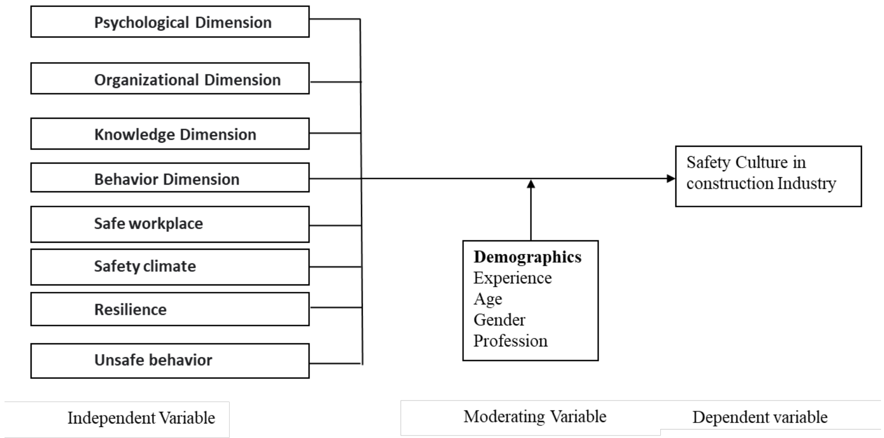

Figure 1: Theoretical Framework

Table 1: Reliability Test

Particular	Cronbach's Alpha if Item Deleted	Remarks
Psychological dimension	0.908	Good
Organizational dimension	0.898	Good
Knowledge dimension	0.901	Good
Behavior dimension	0.898	Good
Safe workplace	0.899	Good
Safety climate	0.902	Good
Resilience	0.904	Good
Unsafe behavior	0.972	Good

The shows the reliability test of individual construct and the overall reliability is found to be 0.91.

RESULT AND DISCUSSION

INDEPENDENT SAMPLE T TEST

An independent sample T test is used to assess the impact of gender groups on the safety culture of the construction sector.

Table 2: Independent sample T Test between Gender Group of Respondent and Safety Culture in Construction Industry

Particular	N	Mean	Std. Deviation	F	Sig. (P value)
Male	33	3.56	0.946	1.817	0.185
Female	11	2.97	0.609	ff	ff

The P value (0.185)>0.05 there is no significant relationship between gender and safety culture in construction industry.

ONE WAY ANNOVA TEST

Since years of experience, age group and profession are used as moderating variables with more than two variables, a one-way ANNOVA test is done to evaluate the influence of these moderating variables on safety culture in construction industry.

Table 3: One Way Annova Test between years of experience of Respondent and Safety Culture in Construction Industry

Particular	N	Mean	Std. Deviation	F	Sig. (P value)
less than 1 year	3	3.8160	0.24966	1.558	0.215

Particular	N	Mean	Std. Deviation	F	Sig. (P value)
1-3 years	14	3.3055	0.68720		
3-5 years	4	4.2344	0.30672		
More than 5 years	23	3.2912	1.06632		
Total	44	3.4173	0.90539		

The P value (0.215)>0.05 there is no significant relationship between experience and safety culture in construction industry.

Table 4: One Way Anova Test between age of Respondent and safety culture in construction industry

Particular	N	Mean	Std. Deviation	F	Sig.
18-30	29	3.4381	0.98945	0.022	0.978
30-45	14	3.3754	0.77454		
Above 45	1	3.3979			
Total	44	3.4173	0.90539		

The P value (0.978)>0.05 there is no significant relationship between age group and safety culture in construction industry.

Table 5: One Way Annova Test between job role and safety culture in construction industry

Particular	N	Mean	Std. Deviation	F	Sig.
Foreman	10	2.683	0.98454	2.556	0.036
Engineer	8	3.8599	0.7439		
Construction Labor	9	3.2032	1.10078		
Accountant/Office Manager	2	3.5240	0.17825		
Plumber/Electrician	4	4.0635	0.18603		
Project Manager	10	3.7517	0.52712		
Environmentalist	1	2.9604			
Total	44	3.4173	0.90539		

The P value (0.036) <0.05 there is significant relationship between job type and safety culture in construction industry.

In general, if the p-value is less than or equal to a predetermined significance level (usually 0.05), then the null hypothesis is rejected in favor of the alternative hypothesis. This means that the observed results are considered statistically significant, indicating that there is evidence to suggest that the relationship between the variables being tested is not due to chance. On the other hand, if the p-value is greater than the significance level, the null hypothesis cannot be rejected, meaning that the observed results are not statistically significant, and there is insufficient evidence to suggest a relationship between the variables.

CORRELATION ANALYSIS

A correlation analysis can only tell whether a strong relationship exists between two variables. But even if a correlation coefficient indicates that a strong relationship exists between two variables, we still do not know the exact shape of the relationship between the two variables. The correlation results were used to answer the research questions or hypotheses.

The table below shows the correlation matrix between dependent variable and independent variables, where, X1 = psychological dimension (Independent variable), X2 = organizational dimension (Independent variable), X3 = knowledge dimension (Independent variable), X4 = behavior dimension (Independent variable), X5 = safe workplace (Independent variable), X6 = safety climate (Independent variable), X7 = resilience (Independent variable), X8 = unsafe behavior (Independent variable), X9 = safety culture in construction industry (Dependent variable).

Table 6: Correlation between Dependent and Independent Variables

	X1	X2	X3	X4	X5	X6	X7	X8	X9
X1	1	859**	.759**	.769**	.731**	.793**	.754**	-0.218	.863**
		0.000	0.000	0.000	0.000	0.000	0.000	0.154	0.000
X2		1	.874**	.892**	.875**	.857**	.862**	-0.173	.957**
			0.000	0.000	0.000	0.000	0.000	0.261	0.000
X3			1	.858**	.933**	.817**	.760**	-0.199	.924**
				0.000	0.000	0.000	0.000	0.195	0.000
X4				1	.932**	.887**	.891**	-0.242	.949**
					0.000	0.000	0.000	0.113	0.000
X5					1	.870**	.804**	-0.251	.938**
						0.000	0.000	0.101	0.000
X6						1	.823**	-0.294	.914**
							0.000	0.053	0.000
X7							1	-0.217	.898**
								0.157	0.000
X8								1	-0.120
									0.439
X9									1

** Correlation is significant at the 0.01 level (2-tailed)

The correlation coefficient of psychological dimension, organizational dimension, knowledge dimension, behavior dimension, safe workplace, safety climate and resilience vs safety culture in construction industry are 0.863, 0.957, 0.924, 0.949, 0.938, 0.914 and 0.898 which means there is positive correlation between these independent variables and safety culture in construction industry. This means that if the industry focuses on improving these variables, it will result in an improvement in the safety culture of the construction sites, which in turn can help reduce the number of accidents and injuries. The corresponding p-value is 0.000, which is less than level of significance (α) = 0.05, signifying that there is significant relationship between these independent variables and safety culture in construction industry.

Whereas the correlation coefficient unsafe behavior and safety culture in construction industry is -0.120 which means there is negative correlation between these unsafe behavior and safety culture in construction industry. This means that if the industry focuses on reducing unsafe behavior, it will result in an improvement in the safety culture of the construction sites, which in turn can help reduce the number of accidents and injuries. The corresponding p-value is 0.439, which is greater than level of significance (α) = 0.05, signifying that there is no significant relationship between unsafe behavior and safety culture in construction industry.

REGRESSION ANALYSIS

Table 7: Regression Analysis of Variables

	Beta	T-value	P-value	VIF
(Constant)	0.618	3.314	0.000	
Psychological Dimension	0.144	4.287	0.000	1.358
Organizational Dimension	0.548	0.691	0.000	1.210
Knowledge Dimension	0.067	2.243	0.000	1.236
Behavior Dimension	0.082	7.071	0.000	1.361
Safe Workplace	0.138	0.963	0.000	1.508
Safety Climate	0.11	1.108	0.000	1.436
Resilience	0.521	9.469	0.000	1.695
Unsafe Behavior	-0.133	-0.147	0.439	1.406
R-square	0.693			
F	109.938			
P	0.000			

The regression coefficient specifies that an increase or decrease in value of 1 unit of independent variable results in beta value increase or decrease in unit of safety culture in construction industry.

For instance, the regression coefficient of unsafe behavior in regression analysis is -0.133 means decrease in value of 1 unit of decrease in unsafe behavior result in 0.133 increase in unit of safety culture in construction industry.

*R*2 value indicates how much of the total variation in the dependent variable is explained by independent variable. Here dependent variable (safety culture in construction industry) is explained by 69.3%. It consists of many other factors as well that influence the dependent variable.

Also, the F value and significance level are 109.938 and 0.000 which states that this regression equation is acceptable.

RESULT AND SUMMARY

Table 8: Summary Result of Hypothesis Testing

Hypothesis	P value	Remarks
Null 1 H_0: There is no significant relationship between psychological dimension and effect on safety culture in construction industry	0.000	Reject
Null 2 H_0: There is no significant relationship between organizational dimension and effect on safety culture in construction industry	0.000	Reject
Null 3 H_0: There is no significant relationship between knowledge dimension and effect on safety culture in construction industry	0.000	Reject
Null 4 H_0: There is no significant relationship between behavior dimension and effect on safety culture in construction industry	0.000	Reject
Null 5 H_0: There is no significant relationship between safe workplace and effect on safety culture in construction industry	0.000	Reject
Null 6 H_0: There is no significant relationship between safety climate and effect on safety culture in construction industry	0.000	Reject
Null 7 H_0: There is no significant relationship between resilience and effect on safety culture in construction industry	0.000	Reject
Null 8 H_0: There is no significant relationship between unsafe behavior and effect on safety culture in construction industry.	0.439	Accept

The study highlights the importance of assessing safety culture in the construction industry using a mixed-method approach that includes both quantitative and qualitative methods. By identifying safety-related problems, interventions can be developed to improve safety culture, which is a predictor of safety behavior and outcomes. However, the questionnaire revealed that various unsafe behaviors were performed by workers on a day-to-day basis, compromising safety and leading to injury or even fatality. These behaviors include ignoring safety equipment, disregarding safety precautions, not paying attention to rules and procedures of workplace safety, skipping daily safety work meetings, and not providing safety suggestions to the supervisor or the team. Unfortunately, workplace safety culture in Nepal is still developing, and many people lack a strong motivation and understanding of why safety is of paramount importance. Employers do not prioritize safety orientation and training, and the government does not have proper OHSA guidelines in place. Moreover, some workers think that wearing safety equipment like hard hats and boots makes them uncomfortable for work and choose not to wear them. Additionally, some individuals lack good judgement and engage in risky activities without realizing the irreparable damage that can be done to workplace safety. It is crucial for these individuals to understand the consequences of their actions, as their behavior can hinder efforts to induce and refine a culture of safety in the workplace.

CONCLUSION AND RECOMMENDATIONS

The study examined a model for a realistic construction safety culture that could help contractors in their efforts to enhance all-around site safety. The results show that the proposed model is sound and that there is a statistically significant relationship between its various components. Various factors like psychological dimension, organizational dimension, knowledge dimension, behavioral dimension, safe workplace, safety climate and resilience show significant relationship with safety culture. Hence, a commendable amount of work should be done in these factors by the organization to further increase safety. Safety is of paramount importance for every age and gender group, but the importance of safety is more to certain profession groups as interpreted by the results. So, people who are directly involved in the construction activities are more vulnerable than those who manage these projects. Therefore, an extra amount of care and precaution must be taken. Unsafe behavior is one of the main factors which directly leads to accidents, hence proper training and research must be done so that workers don’t involve themselves in these activities. Construction is a collective work done by a group, negligence of one person or a group directly impacts the health and safety of other. So, paramount importance must be given to safety which is directly proportional to the culture of industry.

Future research can solve many problems that are related to the study that was given. The suggested model in the current study was validated using a convenience survey (i.e., nonprobability), which was employed to collect data. The most popular technique for assessing safety culture is non-probability surveys (Choudhry et al. 2008; Ojanen et al. 1988). The generalization of nonprobability survey results, however, is debatable (Abowitz and Toole 2010; Al-Bayati et al 2018). Therefore, future research should complement and validate the current findings by combining longitudinal field observations with quantitative and qualitative research (i.e., mixed approach). In fact, the necessity of mixed research methodologies for validating the results of construction research is stressed by Abowitz and Toole (2010) and Al-Bayati et al. (2018). The obstacles faced by the stakeholders in the construction industry in creating, sustaining, and reinforcing a strong safety culture may be revealed by such an attempt. Future work should concentrate on conducting field tests with construction professionals to assess the acceptability, usefulness, and simplicity of the suggested model in comparison to other models already in use by the sector. Future research must also consider the distinctive features of the construction industry. For instance, most construction sites employ numerous contractors and subcontractor organizations, all of which have different perspectives and safety procedures. Future studies could therefore consider the linkages between the safety climates of the contractors and subcontractors in the construction industry.

Even though the research has tried to improve the current safety performance in Nepali construction firms, there are several restrictions that may prevent the research's findings from being simplified or used widely. First off, because the research was carried out using a convenience sample technique just within the Kathmandu valley, results cannot be generalized as representative of the total population of the entire nation. In that sense, data from every province in the nation might be collected by future researchers, leading to more precise results. Second, "Class A" and "Class B" construction firms accounted for most respondents. The analysis of these circumstances may have a different impact on the predictors of "C & D class" Nepali construction enterprises. Finally, this research highlights the need for further exploration of the topic from various perspectives. Potential avenues for future research could include examination of variables such as salary and gender-specific roles as moderators of the relationship between dependent variables. It is also recommended that future studies consider additional factors, such as safety attitudes and safety budgets, to enhance the accuracy of predicting safety culture in the construction industry, even though the current study utilized multiple determinants in its assessment.

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SAFETY-I AND SAFETY-II: CONTRIBUTIONS OF UAS SAFETY MONITORING ON CONSTRUCTION SITES

Roseneia Rodrigues Santos de Melo[1] and Dayana Bastos Costa[2]

ABSTRACT

Unmanned Aerial Systems (UASs) have been incorporated into safety management systems to facilitate hazard identification and propose corrective actions on time, meaning practices related to the Safety-I approach. However, its impacts on understanding and dealing with everyday operations in front of adverse conditions, meaning Safety-II practices, are still unknown. Thus, this study investigates the contribution of safety monitoring using UAS to support Safety-I and Safety-II practices in everyday operations. Two case studies in construction projects were conducted, involving the following steps: (a) proposition of UAS monitoring protocol integrated into safety management routines; (b) field tests to monitor safety performance using UASs; (c) data analysis considering Safety-I, Safety-II and Resilience Engineering. As a main result, resilience mechanisms were identified, such as adaptation in the lifeline safety systems, use of photos and videos to improve workers' awareness, and collaborative work between frontline workers. Regarding the Safety-I approach, most of the identified non-conformities were classified as precarious structures on the construction sites, failures in the Personal Protection Equipment (PPE) use, and safety barriers. The perceived limitations emphasized the difficulty in promoting corrective actions due to the lack of flexibility in the constructive processes, availability of resources timely, and absence of slack.

KEYWORDS

Construction sites, safety management, resilience engineering, and digital technologies.

INTRODUCTION

Safety monitoring in construction sites could be considered a complex task due to the many activities that happen simultaneously and the few safety professionals performing them. This complexity becomes even more prominent without adopting digital technologies to monitor working conditions (Guo et al., 2017). In addition, safety professionals faced some issues in inspection routines that imply the difficulty of timely decision-making, such as the high amount of work required for manual data collection and processing, the lack of standardized safety procedures, and poor communication between teams (Cheng and Teizer, 2013; Lin et al., 2014; Rey et al., 2021).

To improve such aspects, previous studies proposed using digital technologies to identify unsafe conditions, streamline data collection and processing and provide real-time information (Lin et al., 2014; Guo et al., 2017; Awolusi et al., 2018). Among the technologies applied to safety monitoring, the Unmanned Aerial Systems (UAS) must be highlighted due to their ability

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to collect high-resolution visual data, monitor large construction sites, and access hard places in less time and at less cost (Melo et al., 2017). Melo et al. (2017) and Martinez et al. (2020) discuss that the use of the UAS facilitates the visualization of hazards and the inspection of safety regulations on construction sites, especially in situations related to the absence of Fall Protection Systems and inefficient use of Personal Protective Equipment (PPE). Based on the irregular situation identified on-field, safety professionals propose immediate or corrective actions to mitigate or eliminate the risk of accidents visualized by UAS (Melo et al., 2017; Rey et al., 2021).

Despite the potential gains related to the use of UAS for safety monitoring, most studies focus on reactive actions (Melo et al., 2017; Martinez et al., 2020; Kim et al., 2020; Rey et al., 2021) since they aim to prevent something negative from happening, Safety-I approach (Hollnagel, 2014). To cope with this matter, Safety-II emerges as a new way to see and understand safety management. Safety-II believes that to improve safety performance is necessary to look at things done correctly in daily operations rather than just looking at errors and unwanted events (Hollnagel, 2014; Wahl et al., 2020; Martins et al., 2022).

According to Martinez et al. (2020), Rey et al. (2021), and Lima e Costa (2023), the UAS could be used for safety planning, construction site monitoring, and risk assessment. However, none of these studies showed the contribution of UAS safety monitoring to improve everyday operations considering Safety-I and Safety-II perspectives. Therefore, this study aims to investigate the contributions of UAS safety monitoring to support Safety-I and Safety-II practices in daily operations on construction sites.

SAFETY-I, SAFETY-II, AND RESILIENCE ENGINEERING

The Safety-I approach promotes a bimodal view of how work is performed. According to this perspective, operation success occurs because the system works as it should, and people work according to procedures. The failures are usually associated with errors, deviations, and system malfunctions (Hollnagel et al., 2015). This approach does not consider complex socio-technical systems' dynamic and non-linear nature (Wahl et al., 2020). Therefore, it is necessary to adopt other strategies to improve safety performance on construction projects.

In this context, Safety-II seeks to understand how people adjust their actions when they face a critical situation to achieve desirable results (Hollnagel et al., 2015; Wahl et al., 2020). According to the Safety-II perspective, positive and negative effects are possible, which makes it necessary to recognize the risks and opportunities of everyday operations (Hollnagel et al., 2015).

According to Hollnagel (2014), Safety-I and Safety-II perspectives might coexist in the same environment, and the balance between them is essential to move toward a resilient performance. Resilience is the intrinsic ability of an organization to adjust its functioning prior to, during, or following changes and disturbances so that it can maintain required operations, even after an unexpected event or in the presence of continuous stress (Hollnagel, 2014).

Resilience emerges from the performance adjustments carried out by people by themselves or by a group, as characterized by Hollnagel (2018). However, the technical, technological, and organizational factors are also essential to support this adjustment (Heggelund and Wiig, 2019).

Some researchers have been seeking to identify the actions and characteristics that influence performance adjustments, characterized as resilience mechanisms or skills (Hollnagel, 2014; Saurin et al., 2014; Heggelund and Wiig, 2019). The resilience mechanism could be interpreted as actions or strategies to deal with the factors that restrain daily work. Wachs et al. (2016) pointed out some examples of "work restrain," such as the limitations of resources or unavailability (labor, equipment, and materials), incomplete project information, high workload, excessive administrative activities, time limitations, and casual incidents. Regarding performance adjustments, Hollnagel (2014) classified them as actions to maintain and create good working conditions; compensate for something missing, such as replacing materials; and propose solutions to avoid future problems, such as updating procedures.

Wehbe et al. (2016) argued that team discussions about safety conditions, team communication, and collaboration support resilience, even as the efforts to propose actions that prevent an error from recurring. Thus, the lack of resolution to correct the non-compliance compromises resilient performance.

As a practical example, Peñaloza et al. (2017) analyzed frontline workers' behaviors in the precast concrete assembly process and noted some resilience mechanisms, such as team discussions about the set of maneuvers required to reduce risk exposure (compensating); the adoption of strategies to deal with rework (creating conditions); and the practice of avoiding activities that bring a high level of uncertainty (avoiding future problems).

During the evaluation of the safety management system, Peñaloza et al. (2020) emphasized that the compliance indicator and safety checklist, the standardized data collection routines, and the involvement of safety and production professionals in safety conditions assessment and planning could be practices managing complexity. Aiming to incorporate Safety-II practices in construction projects, Martins et al. (2022) proposed a framework based on Safety-I and Safety-II concepts. In this framework, Safety-I refers to work as imagined, and it's established in the form of safety procedures. In contrast, Safety-II relates to work as done, and it's assessed by the monitoring of the constructive processes.

Therefore, despite each approach seeing safety in a specific way, Figure 1 shows they are not mutually exclusive but complementary (Hollnagel, 2014; Wahl et al., 2020; Martins et al., 2022). This means that they must be combined to promote a balance between safety practices and procedures, aiming to increase learning with daily work (Wahl et al., 2020; Martins et al., 2022).

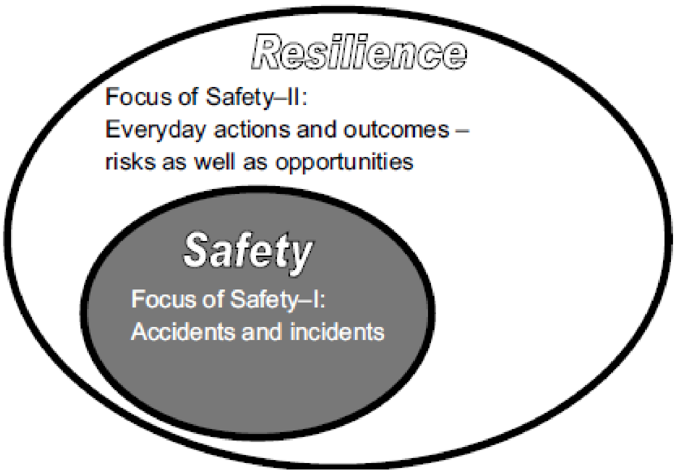

Figure 1: Relationship between Safety–I and Safety–II Source: Hollnagel (2014).

RESEARCH METHOD

This research adopted Case Study as the research strategy, which is a method that emphasizes the real-world context in which phenomena occur (Yin, 2014; Flyvbjerg, 2011). In this study, the phenomenon studied refers to implementing the UAS safety monitoring by adopting Safety-I and Safety-II approaches. The research process was developed according to the following stages: (a) proposition of UAS monitoring protocol integrated into safety management routines; (b) field tests to monitor safety performance using UASs; (c) data analysis considering Safety-I, Safety-II, and Resilience Engineering.

An exploratory case study was developed in Project A, aiming to understand the safety routines through document analysis, interviews, and UAS data collection. Based on this study, a UAS safety monitoring protocol was proposed to be implemented into weekly safety routines to support data collection and analysis (Figure 2). Case studies B and C lasted for 34 weeks and 21 weeks, respectively. During this period, the researcher performed 55 monitoring using UAS technology. Both studies are residential projects for the middle and low-income housing sector. The main construction methods were a continuous flight auger foundation and a cast-in-place concrete wall system. Table 1 describes the primary features of the projects and Flight log data collected in each project.

Table 1: Features of Construction Projects – Case Studies B and C

Case Studies	Project B	Project C
Project features	Land Area: 19,524 m² Total of 380 units Construction time: 16 months Period: Nov/2018 to Oct/2019 34 safety inspections using UAS	Land Area: 16,091m² Total of 300 units Construction time: 14 months Period: Apr/2019 to Oct/2019 21 safety inspections using UAS
Flight Log	Database: 2.210 images Flight time:11 hours and 25 minutes Average flight distance: 1.482 meters	Database: 1.281 images Flight time:6 hours and 19 minutes Average flight distance: 1.340 meters

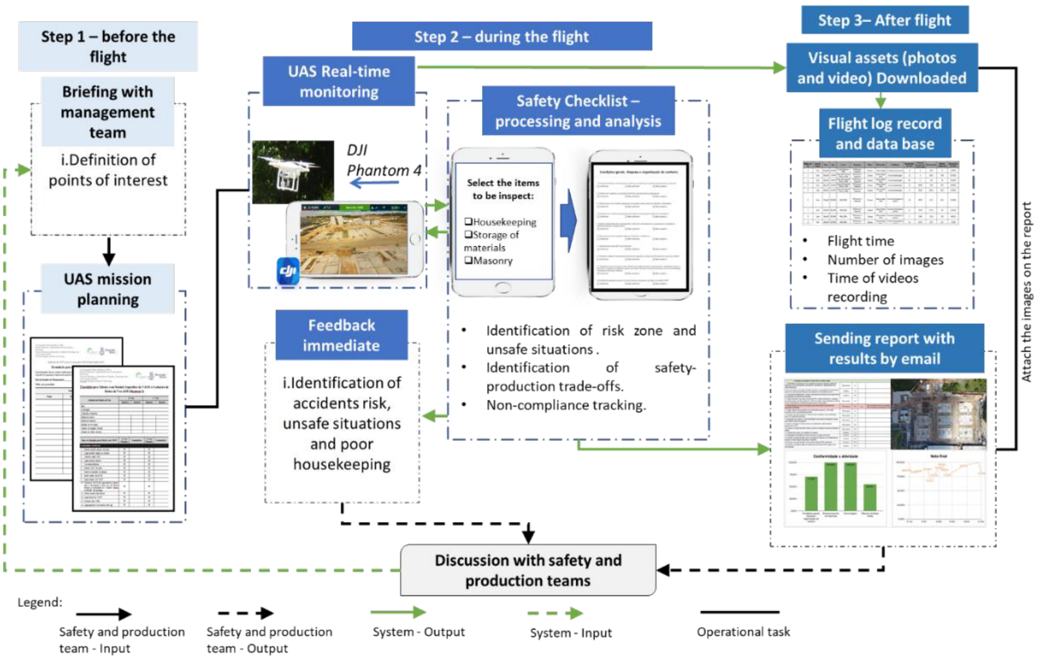

Figure 2: UAS Safety monitoring protocol integrated SMS routines.

During the case studies, the research group automated the safety inspection process, proposing the combination of UAS to monitor safety conditions on-site and a web system to fill out the checklist [OMITTED BY REVIEW]. The UAS safety checklist has 241 items divided into 21 categories (organization and housekeeping, storage of materials, construction site signaling, stairs and ramps, collective protective equipment, and earthwork and foundation). During the monitoring, the pilot controls the drone and gives real-time feedback about the status of each item from the safety checklist for the observer. The observer is responsible to fills out the checklist on the field. In Projects B and C, the safety personnel often participated in the inspections.

The outputs of this phase are the inspection report which contains a safety checklist assessment, the UAS images, and the safety compliance indicator (i.e., the ratio of the sum of compliant items and the sum of items checked). After each inspection, the pilot delivers the report to safety and production teams, including the managers.

The UAS was used to record working conditions, which include non-conformity safety items and informal practices carried out by frontline workers. The inspection report and photos and videos collected using UAS were used in meetings by safety and production professionals to discuss the workplace conditions and production process.

DATA ANALYSIS

Aiming to understand Safety-I practices, it was done a document analysis focusing on operational procedures and a safety checklist, besides the direct observation in safety and production meetings to promote corrective and preventive measures. Two analyses were accomplished based on the UAS safety inspection reports: i) analysis of the safety compliance indicator, identifying the main critical processes and the safety items more recurrent, ii) analysis of non-compliance by constructive process and degree of risk.

From the Safety-II approach, the analysis focused on identifying performance patterns and classifying the system's functional characteristics that contributed to a resilient performance (Wachs et al., 2016; Heggelund and Swiig, 2019). The data collected using UAS were combined with other sources of evidence, such as safety reports, safety meetings, and interviews with safety professionals and civil engineers. A total of nine interviews (a Safety Coordinator, Two Safety Personnel, a Project Manager, a Quality Coordinator, a Production Manager, Two Production Engineers, and a Production Trainee) were conducted to identify the new practices or improvements supported by UAS safety monitoring. The interview data were analyzed using thematic analysis (Braun and Clarke, 2006), allowing for identifying and exploring major themes systematically and flexibly. The thematic analysis considered the following question: *How does the UAS safety monitoring can improve resilience abilities (monitor, respond, anticipate, and learn)?* The codes were extracted by theme and analyzed according to the corresponding mechanisms.

This analysis focuses on two perspectives: i) operational level (i.e., adaptations and actions made by frontline workers to deal with the daily variability); ii) managerial (i.e., decision-making by management teams aiming to improve workplace conditions and avoid non-conformity recurrence). From the operational mechanism, the images and videos collected using UAS were used to recognize adaptation and good practices carried out by frontline workers and production engineers to maintain production workflow. All adaptations were discussed with the safety technician. From the managerial mechanism, the UAS visual assets and the interviews were the primary sources of evidence, and the mechanisms emerged from the thematic analysis.

RESULTS

RESULTS FROM THE SAFETY-I APPROACH

Figures 3 and 4 show the safety performance of Project B and C over time, respectively.

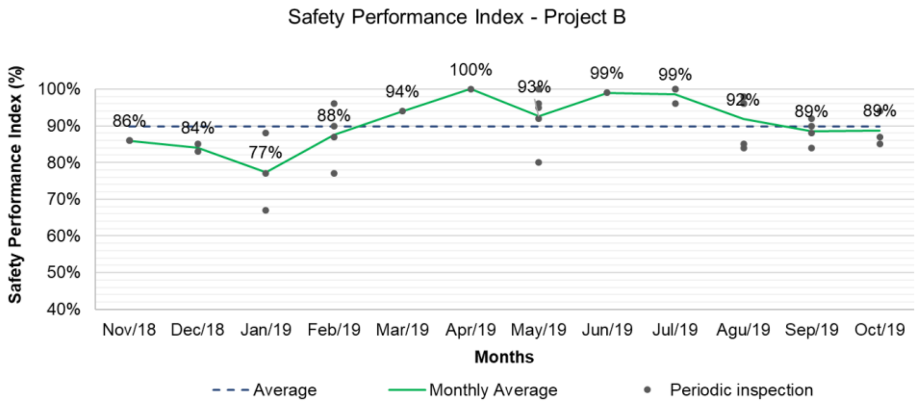

Figure 3: Safety Performance Index of Project B.

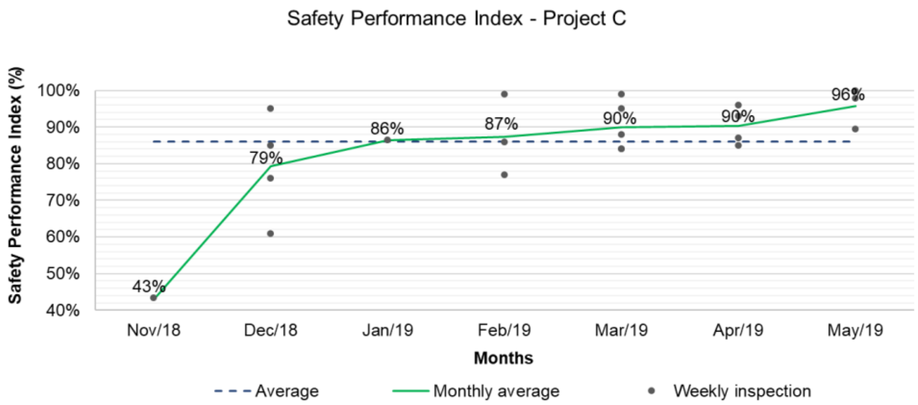

Figure 4: Safety Performance Index of Project C.

In Project B, 1,105 safety items were checked during UAS monitoring, and 102 were classified as non-conformity, corresponding to three notifications per assessment. In Project C, 722 safety items were inspected using UAS, 88 items being non-conformity.

The overall safety performance was 90% in Project B and 86% in Project C. Figure 3 shows that in the first months, the indicator was below the average in both projects, justified due to the lack of safety personnel and the beginning of the site mobilization phase. In Project C (Figure 4), performance improvement is evident over the months, which indicates the team's effort in complying with safety regulations and improving working conditions.

Figure 5 presents the non-conformities by category and by the degree of risk. Regarding Project B, the results indicate that the structural masonry, foundation, cast-in-place concrete wall, and roof had more non-conformities to risk degree 3 (high exposure) than the other processes. Project C demonstrated a similar distribution.

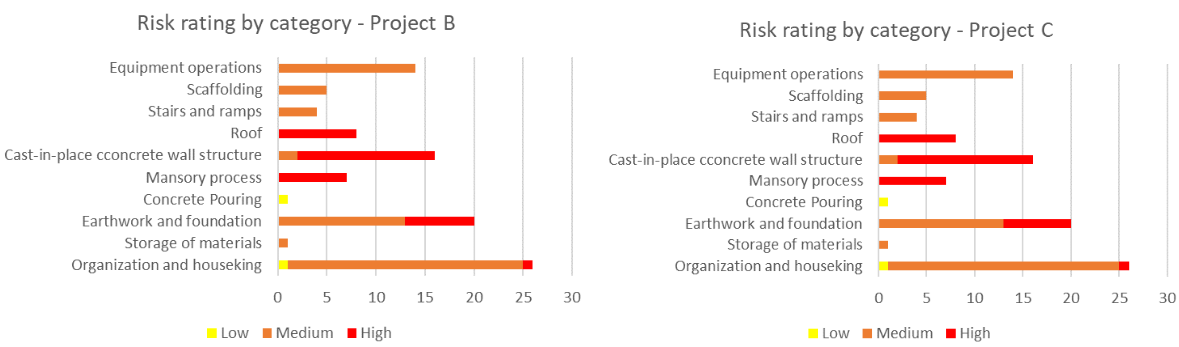

Figure 5: Risk Rating by Category of Projects B and C.

The main non-conformities were: i) waste stored in an inadequate location, ii) lack of signs advertising the risks of the activities, iii) lack of isolation of the cargo handling area, iv) failure in the use of safety belt for working at height, and v) guardrails and safety platforms incomplete or not installed.

In both projects, the number of safety inspections performed increased with the adoption of UAS, contributing to identifying the non-conformities and supporting the corrective measures faster.

RESULTS FROM THE SAFETY-II APPROACH

Table 2 indicates the operational and managerial mechanisms identified in the data analysis. These findings are based on the analysis of visual assets collected using UAS, safety inspection reports, safety and production meetings, and interviews with safety professionals and civil engineers (see the section Data Analysis).

Table 2: Operational and Managerial Mechanisms

Operational Mechanisms	Project	
	B	C
[1] Maintenance of the accesses and internal routes for vehicles and machines to facilitate loading and unloading operations.	✓	✓
[2] Maintenance of the accesses and internal routes for pedestrians, including those not involved in the operations.	✓	✓
[3] Decentralized distribution of materials at the construction site, being them made available at the place of use when necessary.	✓	×
[4] Correct isolation of materials stored in the construction site.	✓	×
[5] Construction of temporary installations (living areas and for storing materials) in regions that do not require repositioning throughout the construction phases.	✓	✓
[6] Marking in the aluminum forms to define the assembly sequence of the parts.	✓	✓
[7] Use wooden structures or metallic guardrails for isolation in excavation areas and work at height areas replacing safety nets.	✓	✓
[8] Adaptation in the lifeline systems connection during guardrail assembly and disassembly.	✓	✓
[9] Use of steel reinforcements as a “barrier” during the guardrail assembly.	✓	✓
[10] Pre-assembly of slab reinforcement and electric installation.	✓	×
[11] Collaborative work between frontline workers during the execution of cast-in-place concrete wall (teams of hydraulics and electric installation, concrete formwork reinforcement, concrete pouring and assembly, and disassembly of collective’s protective equipment).	✓	✓
Managerial Mechanisms		
[12] Use of UAS safety inspection report on daily safety dialogue aiming to discuss the main problems, including housekeeping maintenance.	✓	✓
[13] Use of photos and videos to improve awareness about safety and production routines. Ex. Safety training with technicians about risk perception.	✓	✓
[14] Use of the UAS safety inspection report to promote corrective action on time.	✓	✓
[15] Change in the operational procedures of cast-in-place concrete walls based on photos and videos collected by UAS.	✓	✓
[16] Use of UAS inspection report to evaluate the progress of safety conditions throughout the month and compare it with the safety audit outcome.	✓	✓

The operational mechanisms related to the logistics at the construction site [1-5] appear from the analysis of the conforming items (UAS safety inspection report). It was noted in the UAS safety monitoring and discussed in safety meetings that the safety requirements regarding those mechanisms were always correct. So, they were responsible for maintaining and creating good working conditions. The mechanisms [6-10] were identified during the monitoring using UAS. They were classified as adaptations promoted by frontline workers to compensate for the absence of materials, failures in the lifeline system, and production pressure.

Collaborative work [11] emerge as a mechanism that influences both the creation of good work conditions and compensation for something missing. It was observed in the execution of cast-in-place concrete walls that several teams work together in a restricted space. The results showed that workers helped each other in many moments, for example, during the load of the aluminum forms. In addition, when a team worker was absent, the colleagues did their job to avoid delaying production. Everyone on the team knew to assemble and disassemble the forms of all the rooms.

From the managerial perspective, the safety technicians used the feedback from UAS safety monitoring to discuss with workers the main problems identified, including the ones related to housekeeping [12]. The safety technicians used the feedback from UAS safety monitoring to discuss with workers the main problems identified, especially the ones related to housekeeping [11]. In the same way, the safety coordinator used the feedback provided by UAS monitoring in monthly training carried out with company safety technicians [13]. The use of images and videos about the main problems aims to improve risk assessment and prevent future problems.

The safety inspection report delivered after the UAS flight as well as the immediate feedback (Figure 2) were used to promote corrective action on time [14].

The visual assets were used to promote changes in the execution of the services, especially the sequence of assembly and improvements of collective protection equipment [15]. The feedback provided by UAS monitoring was used to evaluate the progress of the working conditions [16], promoting cycles of learning. The item inspected by UAS monitoring were also verified during the safety audit. Despite being considered a redundancy, this overlap was seen as an opportunity to promote corrective and preventive action in a short time since the UAS monitoring was carried out weekly and the audit only once a month.

DISCUSSION IN LIGHT OF SAFETY-I, SAFETY-II, AND RE

The studies about Safety-I look at errors and non-conformities, blaming the worker for the negative outcomes. While, Safety-II understands that adverse effects are inevitable, and several factors contribute to them due to the complexity and non-linear characteristics of the systems. In this perspective, the worker's participation is indispensable to maintaining operations.

Despite the literature on RE being mature, almost two decades, there is a need to clarify Despite the literature on RE being mature, almost two decades, there is a need to clarify how Digital Technologies (DT) could contribute to a resilient performance. The results show that the UAS safety monitoring supports the identification of nonconformities, supporting decision-making on time. Thus, the UAS monitoring helps understand the types of barriers used and their conditions, allowing the manager to know how much the system operates at the performance limits regarding degraded defenses and barriers.

The visual assets allowed the safety personnel to identify the potential risk of each process individually, especially those regarding work-at-height, the excavation process, and machine operation (such as backhoes, trucks, and cranes). Despite the risk assessment being done before the beginning of the execution, in daily routines, continuous monitoring should be made since new risks could appear from failures in the procedures or the intrinsic complexity of the processes.

Thus, when the information provided by UAS monitoring is only used to promote corrective measures and not to understand what is happening, how the system behaves, and how to avoid the occurrence of new non-conformities, we can say that the Safety-I approach prevails. From the moment that the information contributes to increasing the understanding of how the work is done in practice, it clarifies the adaptations made by frontline workers to compensate for the work limitations, avoiding the occurrence of production disruption for any reason, the system goes towards the Safety-II approach (Provan et al., 2020). Consequently, it becomes more resilient.

According to this understanding of Safety-II and RE, the UAS monitoring furnished visual content to support the discussions between safety and production professionals to promote corrective and preventive actions, encouraging decision-making from different perspectives. For example, interruptions in field activities for correcting unsafe situations, layout changing (storage materials), and use of UAS safety inspection report on daily safety dialogue aiming to discuss the main problems, including housekeeping maintenance.

Safety-II also refers to the learning processes built from previous experiences and knowledge (Hollnagel, 2014). This research found that the UAS monitoring captures the inspector/pilot perspective in the field, which could be mistakes and deviations made, or good practices performed daily. Both case studies used images and videos to disseminate good practice and successful adaptation through training and meeting, especially on the cast-in-place concrete wall process.

While Safety-II practices have been noted, the Safety-I view was predominant. In both case studies, the UAS monitoring has provided helpful information about work conditions. However, the main interest of production engineers and managers was visualizing if the construction site was according to the safety norms. On the other hand, when a non-conformity was identified, it wasn't easy to promote action on time to correct it. This delay or difficulty in acting promptly goes beyond the team's ability to know "when" and "how" to respond. The proposition of corrective measures was influenced by organizational factors, such as the team's technical capacity, availability of resources, the lack of slack in production planning, high productivity targets, and inefficiency in the short term.

CONCLUSIONS

This research aimed to identify the contributions of UAS monitoring integrated into safety management routines for developing resilient mechanisms. The results obtained in Projects B and C show that the UAS monitoring combined with other sources of data and management routines have the potential to contribute to the development and enhancement of resilient mechanisms. Since it improves the system's capacity to monitor the working condition and supports decision-making in a timely manner.

The safety monitoring using UAS made visible both non-conformities and the adaptations performed by frontline workers to deal with work restraint and production pressure. Thus, the visual assets and inspection report proved to be a great source of evidence to be incorporated into the management routines, such as production and safety planning meetings, safety training, risk assessment, the study of critical processes, and layout planning.

From the Safety-I perspective is easy to apply the UAS to identify non-conformity and risk situations in an everyday operation, despite the challenges of using new technology. However, regarding Safety-II further studies need to investigate how to incorporate UAS monitoring into the safety routine to support resilience practices. This is the main defiance since the safety and production professionals need to open their main to look at the adaptations carried out by frontline workers as well as learning with daily practice.

As limitations, the difficulties of accepting new technology from the workers were solved through communication in daily safety dialogues about the use of UAS, the potential risks, and its function. The ongoing work was carried out to raise awareness among engineers and technicians about using images and videos and to use visual assets to improve processes instead of observing people. In addition, the safety professionals argued that the UAS monitoring had low interaction with frontline workers, requiring more routines to integrate them into the monitoring and learning process.

For future research, this paper also indicates the need to investigate using UAS visual assets to support risk assessment and automatic recognition using Machine Learning techniques.

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POTENTIAL APPLICATION OF DEEP LEARNING AND UAS FOR GUARDRAIL SAFETY INSPECTION

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ABSTRACT

Unmanned Aerial Systems (UAS) can provide valuable information about on-site compliance with safety regulations, especially identifying workers in areas without guardrails or fall arrest systems. Despite the advances in using Machine Learning (ML) and, more specifically, Deep Learning (DL) algorithms for detecting safety systems in construction, the literature indicates a gap regarding automatic guardrail recognition. Therefore, this paper proposes a set of criteria for data collecting and processing using UAS and DL for safety inspections in temporary guardrails while producing cast-in-place concrete wall systems. For this research, an exploratory case study was adopted as the research strategy, developed according to the following steps: (a) database image analysis, (b) field study on constructions, (c) formal meetings, and (d) survey carried out with ML/DL specialists. Results show the main failures in guardrails of cast-in-place concrete wall systems, analyzing which can be inspected using UAS visual assets and ML/DL techniques. Also, it indicates the more adequate construction stages to perform safety inspections on guardrails. These findings may guide future research using UAS and DL algorithms for inspecting guardrail safety systems to further contribute to managers' decision-making.

KEYWORDS

Drone, Machine Learning, Construction 4.0, Safety management, case study.

INTRODUCTION

Fall from height (FFH) is one of the main types of accidents in the construction industry (Fang et al., 2018a; Nadhim et al., 2016; Zermane et al., 2023). To avoid FFH-related accidents, a commonly adopted control measure in the Brazilian context (Brasil, 2020; Peinado, 2019) and international context (Baruffi et al., 2021) are collective fall protection systems, such as guardrails. The guardrail system limits workers' movement, preventing them from reaching the area with FFH risks. Despite this, in the 114 FFH accidents analyzed by Zlatar et al. (2019), missing or inadequate guardrails contributed to 65.8% of the cases, positioning this failed measure as the second leading cause, only after the procedure of work, presented in 81.6% of

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the cases. Nadhim et al. (2016) also highlighted that inadequate guardrail systems are among the main factors that cause FFH accidents in construction.

Poor safety is considered waste in the context of Lean Construction (Nahmens & Ikuma, 2009). Waste in production is understood by Ohno (1988) as all activities that add cost but not value. Accidents and injuries are costly in terms of human suffering and affect the level of worker satisfaction and the general well-being of the population. However, they are also financially onerous regarding worker compensation costs, lost time, lost productivity, higher employee turnover, and worker retraining (Nahmens & Ikuma, 2009; Peinado, 2019). During construction activities, monitoring workers and the construction site environment can prevent accidents (Carter & Smith, 2006). Safety monitoring is a critical element of safety management, but this activity is often performed inefficiently. Without adequate technological support, monitoring the entire site becomes an impractical task, given the size and dynamic character of the site (Golparvar-Fard et al., 2009; Guo et al., 2017).

The use of unmanned aerial systems (UAS) (also known as drones) can provide information to improve the safety conditions in construction sites (Costa et al., 2023). The use of UAS to help identify potential risk sites and for safety inspections in building construction has been validated over the last years by the scientific literature, placing it as an essential tool in the context of Construction 4.0 (Rachmawati & Kim, 2022; Costa et al., 2023). Using UAS results in the collection of visual assets allows better visualization of working conditions and, therefore, enhances the improvement of safety inspections at construction sites (Martinez et al., 2020; Melo et al., 2017; Rey et al., 2021).

Considering the large volume of data generated in construction (Baduge et al., 2022) and the limited number of safety professionals on construction site (Kolar et al., 2018), computer vision has been applied to support safety inspections (Akinosho et al., 2020; Pham et al., 2021; Ottoni et al., 2022). According to Baduge et al. (2022), Machine Learning (ML) and Deep Learning (DL) algorithms have been extensively used in the construction industry, addressed to architecture, materials, structures, construction management, progress monitoring, and work safety, among other areas.

The number of publications on work safety in construction applying ML and, more specifically, DL techniques in the computer vision context for detecting safety equipment and systems has increased in recent years (Akinosho et al., 2020; Pham et al., 2021; Ottoni et al., 2022). The papers refer to the automatic detection of personal protective equipment (PPE) (safety belts, hard hats, safety glasses, and vests) and collective protection systems, detection of machines, ergonomics, and positioning of workers, among others (Akinosho et al., 2020; Pham et al., 2021; Ottoni et al., 2022). Kolar et al. (2018) worked on a detection model for guardrail systems. For the training phase of the model, Kolar et al. (2018) used synthetic images resulting from placing the 3D guardrail (developed in Autodesk Revit) in images from the construction environment obtained from Google. The researchers used a dataset with real construction site guardrails images for model validation. Some specifications to be considered in this research: a) Only images from conventional cameras were used for the validation phase, not applying images from UAS cameras, for example; b) only synthetic images were considered for training, assuming that the guardrail will always be visible and without obstructions that compromise its correct visualization, which does not represent the reality of construction sites; c) only one guardrail model was analyzed without further details about the standard supporting its configuration or which construction stages this system is used. Recently, Li et al. (2022) worked on a framework for using UAS and ML to monitor fall hazard prevention systems, such as guardrails. Despite the efforts, the paper focused only on detecting guardrail posts, not considering the entire safety system.

Therefore, this paper proposes a set of criteria for data collecting and processing using UAS and DL for safety inspections in temporary guardrails while producing cast-in-place concrete wall systems. These findings may guide future research regarding using UAS and DL algorithms for inspecting guardrail systems in construction, providing potential problems to be identified, and possible DL techniques for problem automated detection. The primary purpose of pursuing this research field is to support identifying safety systems failures more efficiently and contribute to managers' timely decision-making.

LITERATURA REVIEW

UAS FOR SAFETY APPLICATION

Irizarry and Costa (2016), Costa et al. (2016), and Gheisari and Esmaelli (2019) explored the UAS's potential to inspect safety conditions. The results showed some safety issues, such as inadequate or missing safety guardrails, damaged safety nets, and inadequate scaffoldings. Melo et al. (2017) conducted two case studies at construction sites to assess the UAS applicability to performing a safety inspection, using the visual assets to check the compliance of safety items. The results show that the UAS can provide valuable information about on-site compliance with safety regulations, especially identifying workers in areas without guardrail systems or fall arrest systems. Lima et al. (2021) implemented UAS safety monitoring in a construction site to improve safety planning and control (SPC). The results present that the visual assets collected using UAS could be used to plan preventive and corrective actions, improve the collaboration between the safety and production teams, and increase the transparency of safety conditions.

Through a case study, Martinez et al. (2020) proved that the UAS can support hazard identification and assessment, especially those associated with height conditions, such as missing guardrails and safety nets around unprotected edges, floor openings, and loose or unsecured material at height.

Gheisari and Esmaelli (2018) proposed a workflow using point cloud data generated by UAS to detect the location of the guardrail and openings and then check if they are safety-approved. As a result, they located in a 3D mesh the position of the opening. Mendes et al. (2018) carried out a testbed to evaluate the feasibility of automatic recognition of normative requirements related to guardrails using UAS visual assets. The findings showed that only parametrizable conditions could be inspected through images, lowering the reliability of the algorithm tested (errors close to 20%).

Thus, the literature generally indicates a gap regarding the automatic guardrail recognition integrated with management routines to promote timely decision-making (Mendes et al., 2018; Gheisari & Esmaelli, 2018). According to those authors, the different types of guardrails (color, shape, materials, and geometric properties) are one of the main barriers to automating this process.

DEEP LEARNING FOR SAFETY APPLICATIONS IN CONSTRUCTION

ML algorithms become challenging when working with high-dimension data (Pham et al., 2021). According to the authors, DL algorithms outperformed ML algorithms in safety research once they deal with high-dimensional input data. When equipped with convolutional layers, the DL algorithms become highly efficient in resolving the issue of data sources (e.g., images and videos) (Pham et al., 2021).

Even though the DL has the potential to automate the identification of hazards on construction sites, a fully automatic computer vision-based system still needs to be developed (Fang et al., 2020). Thus, the primary DL technique's challenge is selecting a structure that ensures good performance metrics, such as accuracy and precision (Ottoni et al., 2022), and the fusion of data (e.g., text) with image/video to better understand the nature of the problem (Fang et al., 2020).

Some studies have used DL to monitor safety behavior and identify unsafe conditions on construction sites, especially falling protective equipment (Fang et al., 2018b; Fang et al., 2020; Guo et al., 2020). Kolar et al. (2018) developed a detection model to inspect guardrails by analyzing 2D images captured from construction sites. According to these authors, DL is a promising construction site safety monitoring approach.

However, despite the diverse DL techniques presented in the studies, there is still a gap in testing new solutions to achieve even higher accuracy and fewer false positives for guardrails detection (Kolar et al., 2018).

RESEARCH METHOD

The strategy adopted was an exploratory case study. According to Yin (2018), this strategy aims to identify procedures to apply in future research. The activities performed in this research are illustrated in Figure 1. The following sections describe these steps in more detail.

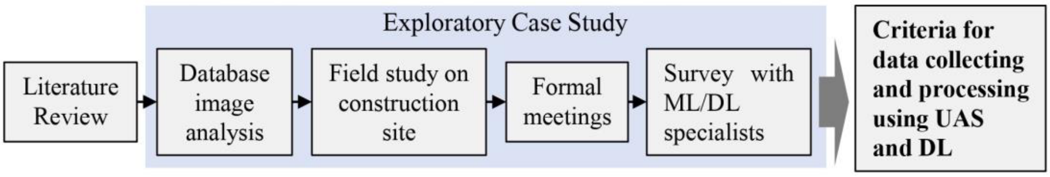

Figure 1: Research Design

CHARACTERIZATION OF THE SAFETY SYSTEMS

In the Brazilian context, guardrail systems are regulated by NR-18 (Brasil, 2020). According to this regulation, the guardrail system can be a solution adopted to prevent workers from falling from height and help avoid the projection of materials in the edge and openings in slabs. If adopted, the system must fulfil measurement, dimension, and load support requirements, among others.

As the formwork system is industrialized, the construction industry has adopted temporary metallic guardrail systems for cast-in-place concrete wall systems. In general, there are two safety systems in this type of construction using guardrails (Figure 2):

The temporary guardrail at the edge of the slab and in the contour of openings in the work area. This system comprises metallic guardrail panels 120 cm minimum high with a toe board supported on the surface (15 cm tall) and guardrail posts fixed on the formwork;

The temporary work platform with guardrails, allowing workers to perform their activities around the story under construction. This system is also fixed on the formwork. The components are work platform consoles, metallic board (floor), metallic guardrail panels with toe board (attending the minimum specifications of the system), and guardrail posts.

Figure 2: Safety Systems with Guardrails in the Construction Site

DATABASE IMAGE ANALYSIS

Ninety images of building construction sites captured using a UAS were selected to identify safety problems in guardrail systems and temporary work platforms. The items specified were considered a problem if they could compromise the correct functioning of these safety systems. These images were obtained from the Research Group database of which the researchers are part. This database has pictures collected using UAS from 9 construction sites. The analysis of the images to create the categories of problems and, subsequently, to identify these problems in each of the photos was carried out by three specialists in Occupational Safety Engineering (OSE) (the first three authors of this paper). The characterization of the OSE is as follows: 1) Civil Engineer, M.Eng., PhD student – 12 years of experience in the construction industry – 3 years of experience in inspections with UAS; 2) Civil Engineer, M.Eng., PhD, Postdoctoral researcher – 8 years – 8 years, respectively; 3) Civil Engineer, M.Eng., PhD student – 6 years – No experience with inspections using UAS, respectively. At least two OSE specialists analyzed each image to ensure that all problems were identified on the images.

FIELD STUDY ON CONSTRUCTION SITE

This stage aimed to identify the production activities of cast-in-place concrete wall structures, including installing and removing safety systems. Two visits were made to the construction site for direct observation of the process and an interview with the engineer responsible for the construction project. The unit case consists of the construction of four buildings in cast-in-place concrete walls of ten floors each, carried out in northeast Brazil. The stages in which the safety systems are installed were identified to determine when UAS flights could contribute to the safety inspection of these systems.

FORMAL MEETINGS AND SURVEY

Formal meetings and a survey were performed to discuss how UAS and ML/DL techniques could work together for safety inspections of guardrails in construction to investigate possible ML/DL techniques to explore these problems and how to standardize the collection of images for better data processing. Five meetings were held, lasting 1 hour and 30 minutes each, with the researchers (OSE) and three ML/DL specialists (ML/DLs). The characterization of the ML/DLs is as follows: 1) Electrical engineer, M.Eng., PhD, Professor, and Researcher – 13 years of experience in the AI area – 3 years of experience specifically in ML/DL-based computer vision; 2) Telecommunications engineer, M.Eng., PhD, Professor, and Researcher – 10 years of experience – 3 years of experience; 3) Electrical engineer, M.Eng., PhD student – 3 years of experience – 2 years of experience.

The survey was carried out with the same three ML/DLs, for each problem type identified in the database image activity. Based on their experience, they were questioned about: 1) The potential for automatically identifying the problems from stage 1 using ML/DL algorithms; 2) What contributes to or limits a problem from being automatically identified by ML/DL algorithms; 3)What ML/DL techniques they suggest for the automated identification of these problems from images collected using UAS; 4) What is the angle of the UAS camera (camera tilt) that they believe to be the most suitable for collecting these images at the construction site (0°, 20°, 30°, 45° or 90° to the horizontal), for further processing by ML/DL algorithms.

To answer the first question, a 5-point Likert scale was used, labeled from 1 to 5, as follows: 1) There is no potential; 2) There is little potential; 3) Not sure; 4) There is a great potential; 5) I am sure ML/DL techniques will identify the problem. The result from question a) was also presented in colors: 1 presented in red, 2 in grey, 3 in yellow, 4 in green, and 5 in blue. The questionnaire was elaborated in Google Forms. Several images were used to represent the problems to be analyzed, and images were collected at construction sites with different angles of the UAS camera.

Based on the previous outputs, the systematization of the results, analyses, and discussions were performed to propose a set of criteria to support safety inspections on construction guardrails using UAS and ML/DL techniques.

RESULTS

TYPES OF PROBLEMS IDENTIFIED AT THE SAFETY SYSTEMS

Based on the analysis of the 90 images from the database by the safety specialists, ten types of safety problems related to temporary guardrails and temporary work platforms with guardrails were identified. The issues and the number of images in which each issue appears are shown in Figure 3.

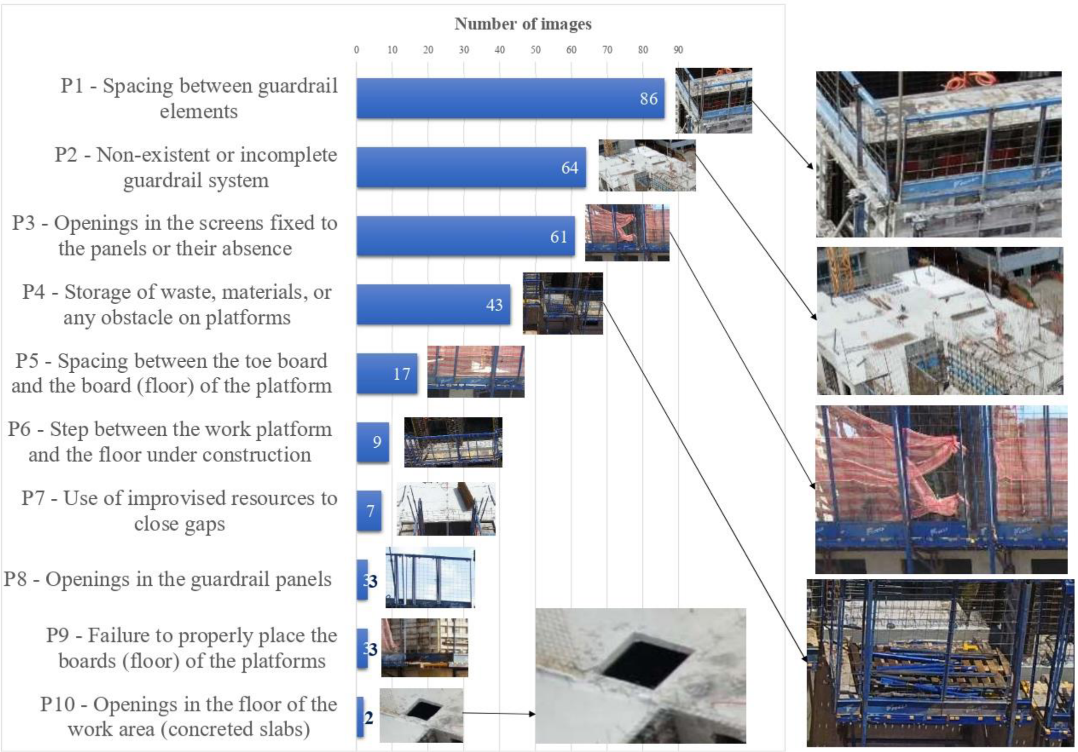

Figure 3: Types of Problems in Temporary Guardrail Systems and Work Platforms

According to Figure 3, problem P1 (spacing between guardrail elements) was identified in 95.5% of the images, while P2 (non-existent or incomplete guardrail system), P3 (openings in the screens fixed to the panels or their absence), and P4 (storage of waste, materials, or any obstacle on platforms) were identified in 71.1%, 67.8%, and 47.8% of the images, respectively. Problems P5 to P10 were identified in less than 20% of the photos.

CONSTRUCTION SEQUENCE TOR THE CAST-IN-PLACE CONCRETE WALL SYSTEM ANALYZED

The sequencing of activities related to the production of the cast-in-place concrete wall system of the unit case is presented in Figure 4. The execution of the structure of each floor occurred in two stages, with side A and side B being built at different times. The company had only a set of formwork (for half of the story). Thus, after concreting the walls on side A and the concrete reached the required design strength (generally around 12 hours), the formwork was removed from side A and positioned on side B. Side B should already have the wall reinforcements, electrical, and plumbing ready to receive the formwork of the walls and continue the activities.

When the forms on side B were removed (after the concrete had hardened), they were taken to the continuity of activities on side A of the upper floor.

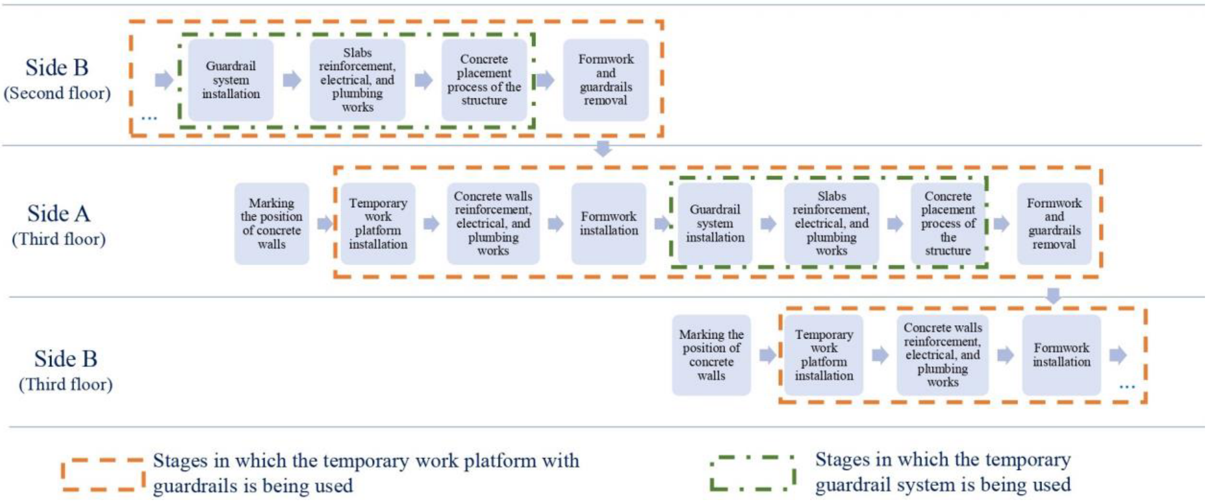

Figure 4: Production Activities of the Structure

Figure 4 shows the activities that integrate the executive sequencing adopted for building each side of the story in the analyzed site. This sequencing was applied from the construction of the second floor to the top floor, in which the installation of the temporary work platform with guardrails became essential. In Figure 4, it is also possible to observe which safety systems were used or were available for use during the execution of each of the activities.

In the process adopted at this construction site, it is observed that only during the activity of marking the position of concrete walls is there no guardrail system or temporary work platforms with guardrails on this side of the construction floor. Lifeline systems were implemented in the construction area for the workers' safety in this activity.

POTENTIAL PROBLEMS TO BE ANALYZED BY ML/DL ALGORITHMS

The ML/DL Specialists' perception of the potential for automated detection by ML/DL algorithms of the ten problems identified in guardrail systems or temporary work platforms with guardrails from images collected with UAS is presented in Table 1.

Table 1: Potential for Automatically Identifying the Problems by ML/DL Algorithms

Problem	ML/DLs 1	ML/DLs 2	ML/DLs 3
P1	4	4	5
P2	4	4	4
P3	4	3	5
P4	2	2	2
P5	2	2	4
P6	2	2	3
P7	3	2	2
P8	2	3	4
P9	2	3	3
P10	4	4	4

ML/DLs = ML/DL Specialists; 1 = There is no potential (red); 2 = There is little potential (grey); 3 = Not sure (yellow); 4 = There is a great potential (green); 5 = I am sure ML/DL techniques will identify the problem (blue).

Based on the evaluation of the ML/DLs, their perceptions converged regarding problems P1, P2, P4, and P10. Furthermore, there was a convergence of two specialists related to problems P3, P5, P6, and P7.

The problems 'Spacing between guardrail elements' (P1), 'Non-existent or incomplete guardrail system' (P2), 'Openings in the screens fixed to the panels or their absence' (P3), and 'Openings in the floor of the work area (concreted slabs)' (P10) were considered with great potential to be detected by ML/DL algorithms from images collected by UAS. According to ML/DLs 2, problems with the image background cleaner (the most explicit image of the problem) contribute to their identification by ML/DL algorithms. ML/DLs 1 and ML/DLs 2 highlighted that the potential for problem detection by ML/DL algorithms increases when these problems are clear and easily identifiable by a person who is not an expert in the field (in this case, in civil construction). ML/DLs 3 also points out that all situations marked with 4 or 5 present images that fit within a pattern. Thus, it is possible to identify the ideal situation and the situation of the problem. Training the ML/DL algorithm with a significant amount of these images will make it more efficient to detect the problems.

The problems 'Storage of waste, materials, or any obstacle on platforms' (P4), 'Spacing between the toe board and the board (floor) of the platform' (P5), 'Step between the work platform and the floor under construction ' (P6) and 'Use of improvised resources to close gaps' (P7) were considered to have little identification potential by ML/DL algorithms. According to ML/DLs 3, for P4, it will be difficult to train the model only to identify materials on the platform. Thereby, materials on the slabs would also be detected, generating numerous false positives. Furthermore, as highlighted by ML/DLs 2, the excess image information harms identifying materials and residues on the work platform. In this case, the specialist pointed out that the work platform's guardrail will negatively interfere with detecting materials on the platform, as it compromises visual identification. Regarding the problem 'Use of improvised resources to close gaps' (P7), ML/DLs 2 highlighted that 'improvised resources' are unspecific and may involve different types of materials to make the inadequate replacement of the guardrail panels. However, for the correct identification of the problem, an image dataset with a recurrence of this problem is necessary for algorithm training.

Referring to ML/DL techniques recommended by specialists, ML/DLs 3 highlighted that there is no simple solution once the variations among algorithms are subtle, mainly for detection purposes. For this specialist, Faster R-CNN has shown better accuracy for practical tests. At the same time, SSD and R-FCN demonstrate a reasonable balance between accuracy and response time (indicated to be used for real-time applications). ML/DLs 1 e ML/DLs 2 also show CNN algorithms. ML/DLs 1 highlights some techniques for classification (VGG16, Inception, Densenet) and detection (Yolo, SSD).

Regarding the angle of the UAS camera to collect images to use in the training and testing of ML algorithms, the three ML/DL specialists converged on the perception that the camera horizontally (0°) or inclined at 20° to horizontally are the most suitable options since it allows easy visualization of problems classified as high potential (4 or 5). Furthermore, two ML/DLs also indicated the 30° angle as a possibility to be explored. Finally, ML/DLs 2 highlighted the use of a vertical angle for the camera (90° to horizontal), as this angle makes it easier to identify the problem 'Openings in the floor of the work area (concreted slabs)' (P10).

DISCUSSION

Based on the constructive sequence presented in Figure 4, using UAS and ML/DL to inspect temporary work platforms with guardrails should be carried out at any time during the execution of cast-in-place concrete wall systems. This flow of activities indicated that at least one side of the building would have this falling protection system installed and used (Figure 5). Regarding temporary guardrail systems, their use appears in specific stages of the work, meaning their inspections will take place at particular stages of the structure's production (Figure 4).

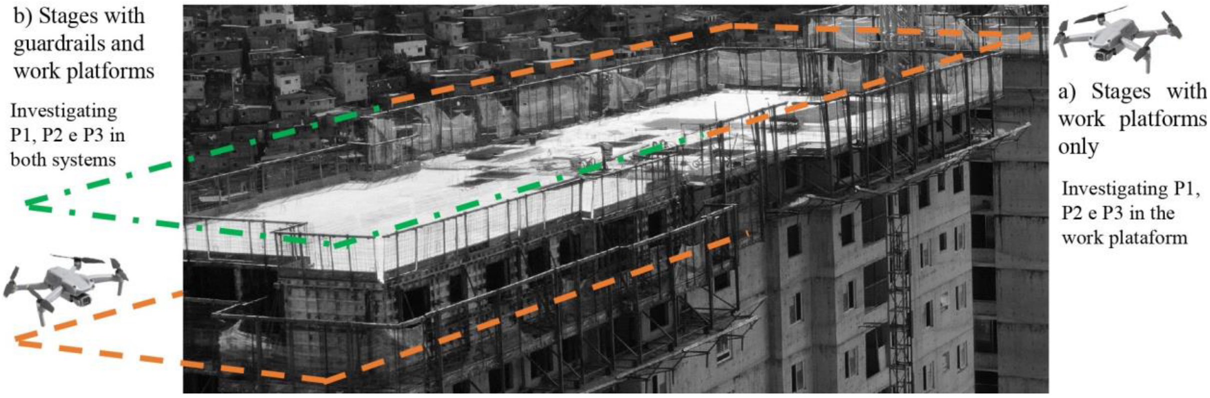

Figure 5: Different Stages for Collecting Data in the Construction Site

This analysis was essential to understand the moments that guardrail inspection should be performed, avoiding unnecessary inspections and consequently reducing non-value-added activities (Womack & Jones, 2003). Thus, the inspection frequency of the safety systems depends on the structure's production rhythm. Therefore, the safety systems should be inspected at a minimum when each story's installation has been concluded.

From the ten problems identified in the falling protection systems used in the cast-in-place concrete wall, problems P1 to P4 appeared more frequently in the images. In contrast, the other problems (P5 to P10) appeared with significantly lower frequency. According to ML/DL specialists' perception of which problems have the most significant potential for automatic detection by ML/DL algorithms, they highlighted: P1 (Spacing between guardrail elements), P2 (Non-existent or incomplete guardrail system), and P3 (Openings in the screens fixed to the panels or their absence). Despite the P10 (Openings in the floor of concreted slabs) being identified by the ML/DL specialists as a problem with great potential to be recognized by ML/DL techniques, it showed low occurrence in the analyzed images. It results in more difficulty using the ML/DL algorithm since there is a need for many images with the referred problem to train it. Thus, this research focused on problems P1 to P3 since they present the most potential to identify using ML/DL and appear more frequently in the images.

Regarding ML/DL techniques, there was a convergence between the recommendations of the ML/DL specialists and the techniques employed and systematized by Pham et al. (2021), Baduge et al. (2022), and, Otonni et al. (2022). Despite the several techniques presented by the ML/DL specialists and in the literature, they mainly focused on using CNN algorithms (a class of DL).

Based on the results and discussion, the set of criteria for data collecting and processing using UAS and DL for safety inspections in temporary guardrails during the production of cast-in-place concrete wall systems is summarized as follows:

The safety inspection with UAS and DL should be performed in some specific stages of the execution of cast-in-place concrete wall systems when the safety systems are already installed;

Ten problems were identified in the safety systems with guardrails. However, only three problems have the potential to be automatically identified by ML/DL algorithms based on the ML/DL specialists' perception and in the occurrence of these problems in the images analyzed, which are: P1 (Spacing between guardrail elements), P2 (Non-existent or incomplete guardrail system), and P3 (Openings in the screens fixed to the panels or their absence);

CNN algorithms (class of DL) should be investigated more for the automated identification of these problems in guardrail systems from images collected using UAS based on the ML/DL specialists' perception and the literature;

UAS cameras should be used horizontally (0°) or inclined at 20° to horizontal for data collecting since it allows easier visualization of guardrail systems' problems for further processing by ML/DL algorithms.

The indicated criteria are important for advancing research involving inspecting guardrail systems using UAS and DL algorithms to further identify these failures with greater efficiency and accuracy. Access to information generated from more agile inspections using UAS and automated detection of problems in guardrail systems (through DL algorithms) may contribute to managers' timely decision-making. This proposition aligns with Principle 8 presented by Liker (2021) regarding technology adoption and adaptation to support people and processes from the organization. In the context of this principle, Liker (2021) highlights that technology has the role of alerting people to problems so they can quickly and creatively respond to them. Based on the experience of Raja Shembekar, Liker (2021) emphasizes that technology provides superior information that enables managers and team leaders to make decisions at a much higher level.

The impacts on visual management are evident once the UAS adds value to the data-collecting process, providing images of the work-in-progress from different perspectives and moving around the construction site more quickly than in conventional situations (Rey et al., 2021; Martinez et al., 2021). In this regard, the UAS combined with ML/DL techniques has the potential to eliminate or reduce the waste of time spent during the inspection, and the safety personnel could be driven to other activities related to workers' involvement and safety culture.

CONCLUSIONS

This research explored the main failures in guardrails of cast-in-place concrete wall systems, analyzing which can be inspected using UAS visual assets and ML/DL techniques. The research has been conducted as an exploratory case study using several sources of evidence, such as questionnaires, database analysis, and direct observation. The results can be generalized to theoretical propositions for similar problems.

The result indicates that four of ten problems (P1 to P4) have the potential to be identified automatically using the ML algorithm. However, this research focus will be on problems P1 to P3 due to the number of images containing the problems. Thus, the discussion defined criteria for data collection using UAS and specified the potential ML/DL techniques used to automatically recognize the guardrails failures during the cast-in-place concrete wall execution. The findings can support the development of a system for automatically detecting safety issues in guardrail systems, which can contribute to managers' decision-making timely related to safety.

Although this research focused on a specific type of guardrail system, this does not mean that ML/DL algorithms could not be applied to other systems. Finally, further studies need to be developed to test ML/DL techniques in this context and propose a method to inspect guardrails using UAS for data collection and an ML/DL algorithm for data processing.

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FEATURES OF A BEHAVIOR-BASED QUALITY SYSTEM (BBQS)

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ABSTRACT

Meeting quality expectations is vital to the successful delivery of construction projects. Still, the levels of quality achieved in practice are often unsatisfactory, resulting in rework or acceptance of poor work, and impacting the project cost, schedule, safety, team morale, reputation of the organizations and individuals involved in the project, and overall customer satisfaction. Quality management research has relied on statistical process control, tolerances, and standards development. In the last years, though, attention has been shifting towards theoretical and philosophical foundations of quality, and the role people play in planning to define quality expectations and achieving them. The contribution to knowledge of this paper is to expand on the literature on Behavior-Based Quality (BBQ) by introducing the Behavior-Based Quality System (BBQS) and presenting some of its features. We present theoretical foundations of this system and illustrate some of its features through a case study. The purpose of this paper is twofold, (1) to promote more systemic thinking about the management of quality, and (2) to present features of a system that supports such thinking.

KEYWORDS

Quality, lean, Behavior-Based Quality (BBQ), Behavior-Based Quality System (BBQS), psychological safety.

INTRODUCTION

Crosby (1979 p. 6) saw quality as a "catalyst that makes the difference between success and failure." The importance of meeting quality expectations is not up for debate; the vast number of research papers and books on the subject are evidence of it. Literature on quality ranges on a spectrum from being technical-oriented to human-oriented. The technical-oriented literature pertains, for example, to tolerances and standards applicable to specific scopes (e.g., Milberg

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2006, ASTM 2020). The human-oriented literature pertains, for example, to management practices (e.g., Crosby 1979, Deming 1986, Juran and Gryna 1988), methods and tools to minimize mistakes due to human error (e.g., Shingo 1986, Godfrey et al. 2005, Tommelein 2019), and the culture and behaviors of those involved in the quality process (Flynn 2001, Thomas et al. 2002, Howell et al. 2004, Pounds et al. 2015, Oakland and Marosszeky 2017, Spencley et al. 2018, Gomez et al. 2019, 2020).

Researchers and industry practitioners proposed Behavior-Based Quality (BBQ) as an approach to quality that highlights the human factor (e.g., to err is human, beliefs) of all people involved in the quality delivery process, from those planning the process to those executing it and assessing whether quality expectations are met. Yet, publications to date describe BBQ's intent but do not expand on how to apply it. The system described in this paper, Behavior-Based Quality System (BBQS), embraces BBQ; specifically, this paper provides a systemic overview of the BBQS and expands on BBQS's features using illustrations from a case study.

LITERATURE REVIEW

QUALITY IN CONSTRUCTION

Crosby (1979) proposed one of the most well-known definitions for quality, "conformance to requirements." He said that requirements need to be "clearly stated so that they cannot be misunderstood." In construction, ensuring that requirements are clearly stated is challenging and time-consuming because of the multiple stakeholders involved in the design and construction of a project. Many associations have developed standards, codes, and regulations that provide valuable information for designing and building construction projects (e.g., Arditi and Gunaydin 1997, ASCE 2012). However, quality issues persist, resulting in rework that can amount to as much as 12% of the total project costs (Love et al. 1999) and delay a schedule by as much as 9.8% from the original target (Dougherty et al. 2012). Despite the need to improve the delivery of quality, Koskela et al. (2019) described a decline in the quality movement due to apparent weakness in the theoretical and philosophical foundations of the subject. With this paper, we aim to contribute further to those foundations of quality.

FROM BEHAVIOR-BASED QUALITY (BBQ) TO A BEHAVIOR-BASED QUALITY SYSTEM (BBQS)

Extensive research has been conducted on Behavior-Based Safety (BBS) in construction (Geller 2001, 2005, Li et al. 2015). A search on the topic of "behavior-based safety" in the Web of Science database and Google Scholar shows 366 and 7,080 articles to date, respectively. BBS foundations suggest that safety on a project can be improved by fostering behaviors needed for safety, such as wearing protective gear or using an equipment guard (Geller 2001). BBQ is built on similar foundations, focusing on behaviors to improve the delivery of quality by fostering alignment and minimizing quality issues once work is built (Spencley et al. 2018).

Spigener (2001) described BBQ as an approach to quality that consists of engaging personnel in quality and fostering the "right behaviors" while moving away from disciplinary actions as tools for improvement. This resonates with Deming's (1986) principle of eliminating fear from the workplace to deliver quality. Researchers explored BBQ and its connection to Lean, especially to respect for people and reliable promises (Gomez et al. 2019, 2020). When managing quality, for instance, Gryna et al. (2005 p. 127) suggested to "treat all people with dignity", which reflects the Lean principle of respect for people. Similarly, understanding, aligning, and meeting certain quality expectations requires making and keeping commitments, which reflects reliable promising (Winograd and Flores 1986, Macomber and Howell 2003).

Over the past two decades, several studies have highlighted the importance of fostering psychological safety in the work environment due to its impact on team performance and learning (Edmondson 1999, Carmeli 2007, Huang and Jiang 2012). In construction projects, performance is measured in terms of cost, schedule, quality, etc. Researchers explored the connection between Lean and psychological safety (Howell et al. 2017, Gomez et al. 2020) and proposed psychological safety as a foundational principle for BBQ (Gomez et al. 2020). Psychological safety for BBQ is viewed from a team perspective (Edmondson 1999, Edmondson and Lei 2014). In construction, a team member is everyone involved in the project delivery, from the client, to the architects who design the project, to the contractors building it. Within a construction project team, psychological safety allows the project team members to (1) talk about mistakes when these occurred instead of trying to hide them, and plan to avoid their reoccurrence, (2) ask questions to clarify expectations before building, and (3) share their concerns when requests are not feasible or achievable within the project constraints, etc.

Crosby (1979) highlighted the need to design systems to manage quality that prevent defects. Gordon et al. (2021) proposed that a more systematic view of BBQ could deliver better project outcomes. However, what such a system might look like hasn't been defined yet. Inspired by Ballard and Tommelein's (2021) work in articulating a benchmark to meet and improve upon, the first author is currently working on research to describe a BBQS and its features. An extensive literature review on quality cannot be presented here due to page length limitations; please refer to Gomez' (2023 forthcoming) dissertation. The following section presents a framing of the features that one might desire to have in a system for managing quality.

WHAT DOES THE SYSTEM LOOK LIKE?

We propose BBQS features while thinking of those doing the job; aiming to facilitate BBQ adoption. The features of the system we propose include:

1. Functions of the system: the job needed in the service of delivering quality
2. Presuppositions to be aware of: assumptions people bring when managing quality
3. Principles and behaviors that are the foundations of the system: the rules of action and the behaviors desired for quality
4. Processes involved: the steps and people involved in delivering quality
5. Methods and tools: methods and tools that facilitate the processes to deliver quality

Table 1 describes the behaviors desired of people using the system to manage quality in their everyday work. In the text that follows we illustrate how these were observed, and what processes, methods, and tools the team used to deliver quality. The remaining features are expanded on in Gomez (2023).

FINDINGS FROM PRACTICE

METHODOLOGY

We used a descriptive case study approach (Yin 1993) to explore some of the system's features and how these may have influenced the quality outcomes. We documented this case after the project was built. The General Contractor (GC) who built it considers it one of their best-in-class projects. This case is a Design-Build (DB) Tenant Improvement project with lab areas, a vivarium, and office spaces. Due to the collaborative nature of DB projects, the GC and trades such as mechanical, electrical, and plumbing, were onboarded during design. In addition, most of the GC' staff had worked together for 1-3 years on another project, prior to this one.

The first author surveyed 22 team members asking questions with responses scored on a 7-point Likert scale. In addition, she interviewed 10 of the same team members, from the architect to the drywall- and taping foremen, and asked them to describe and illustrate the following:

1) What actions did project team members take that relate to BBQ? (2) Did the team use any BBQ processes? Which ones? (3) What methods and tools fit the quality delivery process?

Table 1: Behaviors Desired for Quality in the BBQS

Behavior	Focuses on
Being respectful	Treating others with dignity and courtesy and helping them develop their capabilities (Fuligni et al. 2005, Lalljee et al. 2007)
Active caring	Looking out for the people doing the work and the quality of the work (Roberts and Geller 1995, Randall 2013, Spencley et al. 2018, Gomez et al. 2019)
Making reliable promises	Making and keeping commitments (Winograd and Flores 1986, Stoljar 1988, Macomber and Howell 2003)
Speaking up	Sharing ideas and expressing freely any question, concern, suggestion, etc., relevant to the work in discussion (Premeaux 2001, Hilverda et al. 2018)
Being diligent	Being careful, probing, not just accepting information or resources given, as is, without checking (Bernard et al. 1996, King et al. 2012, Powell 2017)
Active listening	Trying to hear not only the words that are said but the message being communicated (Bodie 2011, King et al. 2012)
Active learning	Applying the Plan-Do-Check-Act (PDCA) cycle of continuous improvement (Edmondson 1999, Kostopoulos et al. 2013)

The examples illustrated in this paper focus on drywall installation and are part of a larger study in progress. However, our hunch is that many of the features described are likely applicable to other scopes of work as well. We explore the team's psychological safety as a preamble to analyzing the features of the system in a context.

TEAM PSYCHOLOGICAL SAFETY

The GC's leadership described this team as a high-performing team. In this case, we hypothesized that the team members would show high psychological safety due to the relationship described in the literature between psychological safety, learning, and team performance. Indeed, all participants interviewed reported feeling psychologically safe to speak up and share their mistakes so that the whole team benefited from it and learned together.

"I believe we make it safe for everybody to discuss." – Drywall Project Manager (PM)

"We can rely on one another. We admit our mistakes and shortcomings." – Architect

"I'm not shy reporting any mistakes that I make, and no one here is... Everyone can speak up here." – GC Assistant Superintendent

Early in the project, the project team hosted a series of team building workshops provided by an external consultant. All the staff members who were onboarded at that time were invited to participate in these workshops. The consultant assessed each member's personality and used their responses to help them get to know each other better.

"From the profiles that [the consultant] generated, he was able to say, 'you are this kind of person, you'll say hi to everyone, and you'll do this or that.' It really helped us all to understand people better at those early stages in the project." – Architect

Although these workshops were held only at the beginning of the project, the team continued organizing activities such as happy hours and team lunch-and-learn sessions to continue strengthening the relationships between them, especially with those who joined the project later.

Through the survey, we also explored whether there was any difference between how psychologically safe craft and staff team members felt. Table 2 shows that craft scored lower; therefore, an opportunity exists to foster psychological safety more at the craft level. The drywall company belongs to the GC, so craft workers may tend to have longer job tenure, and any improvements would benefit the team in the short- and long term.

Table 2: Team Psychological Safety for Craft and Staff (1=low, 7=high psychological safety)

Psychological Safety in Relation to	Craft Perception	Staff Perception
Team leader/supervisor	5.418	6.720
Peers/other members of your team	5.947	6.500

We speculate that the staff-craft gap in psychological safety may have a connection with (1) staff members receiving more people skills training and opportunities to connect at a more personal level, (2) experiences where craftworkers were mistreated, yelled at, sent to do most tedious work in retaliation of a mistake they made, (3) craftworkers being paid hourly may feel that their jobs are more instable and avoid taking interpersonal risks for self-protection, etc.

TEAM BEHAVIORS DESIRED FOR QUALITY

We present evidence of the BBQS behaviors as described by the project team members:

Being Respectful

Participants reported being treated with respect and receiving opportunities to keep developing their capabilities. The Lean principle of respect for people is reflected in the team's effort to learn to appreciate diversity and be aware of other team members' perspectives while helping them continue expanding their technical knowledge.

"All the ideas were always heard, whether you were an engineer or a manager, everyone was heard equally, and I'd say that as a great sign of respect… [when using the layout robot, the GC asked users:] Did you feel it was useful? Was it confusing to you? What else do you think we should layout with this?... there was definitely a lot of feedback after each area [was completed], and we kept iterating the [layout] process to make it better and more useful." – Virtual Design and Construction (VDC) Engineer

Active Caring

Participants described many actions the team took showing active caring, e.g., by preventing or minimizing trade damage to the extent possible, and engaging team members in quality conversations. The team hosted conversations about so-called Distinguishing Features of Work (DFOW) for various scopes of work; drywall was not one of them, but still, they planned the scope well, heavily relying on the experience of the drywall division.

> *"This is the first job where I found it easy to find the information we needed... The GC superintendent helped us a lot in that aspect; all walls had QR codes with all relevant information [we needed to build]." – Drywall Foreman*

> *"It was refreshing having a young, energetic team that was out there to do a great job." – Architect*

MAKING RELIABLE PROMISES

Participants reported doing well in making and keeping promises, e.g., agreeing to apply level 5 finish to a drywall wall, considering the resources available of manpower and time required to complete the work as per the acceptance criteria.

> *"We are good about saying when something is not achievable. They [other team members] might not agree with this, but there it is." – Drywall PM*

> *"On this project, requests were talked about in our group; sometimes [the GC] would say this area has to be done tonight, then we would talk about it, [and make a*

counterproposal], and we would agree to finish half of it that day and the rest the following day." – Drywall Superintendent

Speaking Up

Participants reported being confident when expressing their thoughts, concerns, questions, etc. We noticed, however, an overreliance on others to speak up. As shown in Table 1, craft felt less psychologically safe than staff members; being deliberate in designing means for craft members to communicate with minimal or no barriers could help them speak up.

"I like to ask; I prefer to ask or be asked rather than having to do the thing again." – Drywall Foreman

"Most people have felt empowered to say, 'I think I've got an issue here; can I just talk to you about it?', even if it's just as simple as: 'am I being crazy?', can you just take a look at this real quick one?" – Architect

Being Diligent

Participants described in detail the process they followed in planning and building for quality. For instance, typically checking the information to ensure it is complete, accurate, etc. In the field, similarly, checking expiration dates, materials, etc. Diligence requires being constant. Even when things are going well, it is important to keep checking and not become complacent.

"I dedicate myself to doing QC and making sure we don't miss things." – Drywall Foreman

"We did two weekly office hours… we sat down and went through any open questions; like there is a window here and you can get daylight on this wall, so we're going to see any imperfection [due to light conditions on the wall so this wall better have a level 5 finish]." – Architect

Active Listening

Participants reported they tend to pay full attention to the speaker, trying to understand what this person says, and what not.

"Our team does a really good job, we've got experienced people, but they don't let their ego or pride get in the way, and they are willing to listen." – Drywall PM

"If you have an idea to share, everyone listens and pays attention. If you have a problem, you'll get an ear to listen to you." – GC Assistant Superintendent

Active Learning

Participants described strategies they took to learn, from experimenting with the layout robot to documenting quality issues on PlanGrid. The team could use, however, a strategy to analyze root causes, such as 5 whys or cause mapping, to avoid having the issue reoccur.

"Everyone was very open to trying new processes, or innovate, and make something better… For the robot, we had a lot of iterations on what was good, what was not useful, and what was actually not good at all and confusing to people." – VDC Engineer

"When we find a mistake on a floor, we try to avoid it on the upper floors… Still, we've had repeating mistakes that occurred. It wasn't a lot but some stuff that slipped our minds… During the daily rush that we have in the field, it's impossible to follow [remember] all the lessons learned." – GC Assistant Superintendent

PROCESSES

The quality process, from design to production, requires multiple steps and involves many people. We limit our description of this section to subprocesses that the team thought really helped them manage quality beyond their typical practice.

User Flythrough Sessions

These sessions were an extension of what is typically done in BIM coordination. In these sessions, the focus was on including the end-users in the model review. End-users had the opportunity to virtually see what the requirements in the project drawings and specifications look like when built. This project had four different user groups (1) environmental health and safety, focused on constructability and safety, (2) biology lab users, focused on lab usability, including, for example, applicable requirements for their lab equipment, (3) vivarium lab users, also focused on lab usability, and (4) general facility management, focused on accessibility and maintenance. All these groups participated in the flythrough sessions and provided feedback.

Distinguishing Features of Work (DFOW)

The GC introduced the DFOW process to the client, architects, and trade partners early in the project. Even though no specific DFOWs conversations were scheduled for drywall work, the project team had conversations about various aspects of that scope during construction:

> *"[we talked about] what's coming up that they need our input on; for example, we're going to be building this feature wall next week; what do you want to see? When do you want to come and take a look at it? What kind of things are you concerned about here? Are there any details or junctions that drywall needs to pay attention to?" – Architect*

Trade Damage Control

Trade damage is a tough topic of conversation between subcontractors. Typically, the amount of damage is assessed and allocated to subcontractors, based on the number of people they had on the project, when the GC is closing out contracts. In this case, the team defined a process (Figure 1) that allowed them to distribute damage costs monthly. Doing this periodically allowed them to accurately assess whose responsibility it was and provided cost clarity for trades since they were getting monthly updates regarding their portion of the costs.

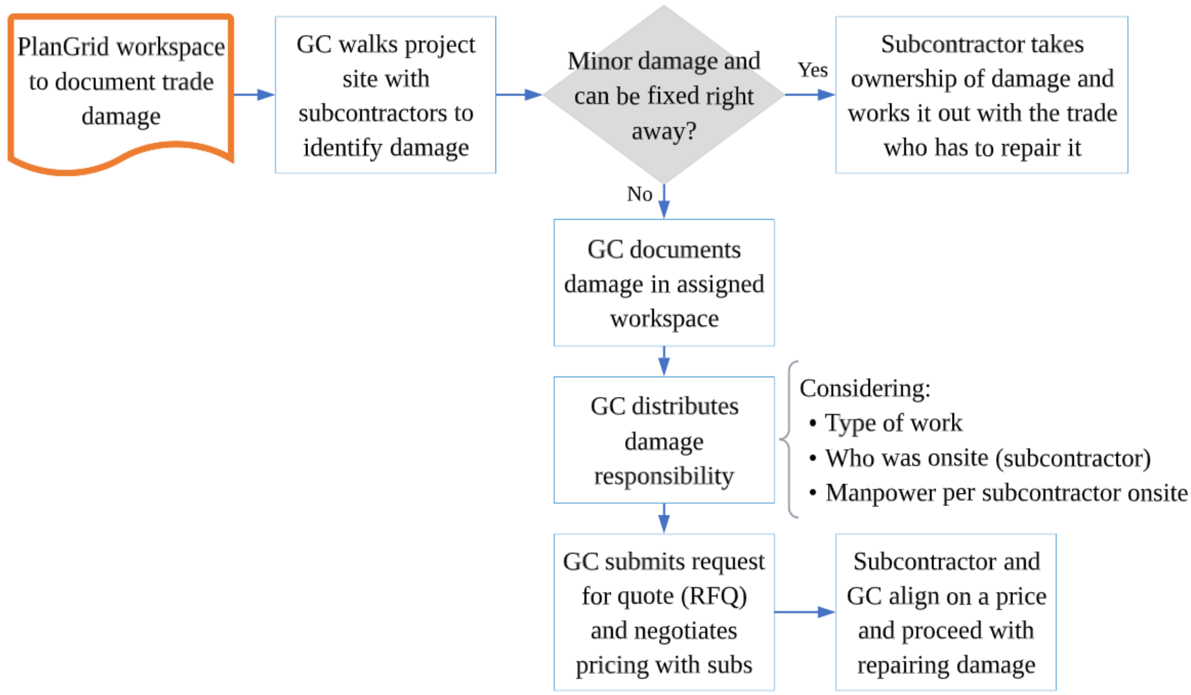

Figure 1: Quality Control: Trade Damage Management Process

The process established by the team resulted in a better distribution of damage costs:

> *"We have the biggest crew on the jobs, so we have the most manpower. In past projects, trade damage costs would be divided based on how many men you had on the job, so we would have the highest trade damage cost. Here [the GC] didn't do that. The GC took the daily reports to figure out who was in the area [assigning the damage to the ones who caused it]." – Drywall PM*

Architect Site Walks for Quality Control

The architect participated in scheduled walks to provide feedback on the acceptance of work throughout construction.

> *"We did regular walks once or twice a week with GC superintendents and produced weekly architectural field observation reports. Those walks and the field observation reports were used for corrective action with the trade partners" – Architect*

Methods and Tools

This section describes the project-specific methods and tools used to support the delivery of quality.

Automating Walls Layout

The GC used a robot they designed themselves to print layout information on the floors (from a CAD file), using lines, symbols, and different colors and inks as needed. This robot was first used on a large scale on this project. The robot laid out things that contractors needed with greater detail and faster than the manual layout.

> *"We had four lines for each wall [Figure 2]. So, if a pipe has to go exactly in the center of a wall, you'll have laid out one layer of sheetrock or two layers of sheetrock [to see verify pipes don't clash with the drywall board]." – VDC Engineer*

Figure 2: Wall Layout Painted on Floor Slab by Robot

Lean methods and tools involved in the adoption of this automated process include, for example, (1) mistakeproofing by using one specific ink color on the floor per contractor, so they do not get confused with the lines of other contractors, (2) visual management by printing the lines of each drywall board to be installed, so things that are to be embedded on the wall such as pipes do not clash with where the wall is to be installed, and (3) PDCA and collaborative design of operations by gathering feedback from the users (craft and foremen) to improve the use of the robot to better suit the needs of the field.

Facilitating Information in the Field through Dynamic QR Codes

The superintendent, who struggled on previous projects having to search more than a dozen drawings to inspect the work on one wall, developed an initiative that the GC carried to other projects after the success of this case. This initiative consisted of developing PDF packages with all relevant information to build and inspect a wall, and post these packages using dynamic QR codes in the field. Anyone on the project with a smartphone or iPad could use the QR code and access the information package. Each package included, for example, the architectural plan, electrical, mechanical, and piping plans, lighting plan, snapshots of the 3D model, and elevation views. Dynamic QR codes allowed the team to modify the content in each package without replacing the physical QR code posted onsite.

> *"The superintendent used it [QR code] a lot because every time she walked; she could say 'hey you can't close this wall because something is missing here.' Once you close the wall, there is a lot of rework. Compared to her previous jobs, where she had to open the wall for changes, here we had very few cases where we had to open something for a change." – VDC Engineer*

Before closing walls, the GC's assistant superintendent walked the site to inspect the work and took pictures of where the pipes were located (Figure 3). When a wall is closed up, and some other contractor or the owner needs to install something and screw something into the wall, they know exactly where the pipe is located and can avoid damaging the pipe by drilling into it.

Lean methods and tools for such information available include, for example, (1) visual devices comprising QR codes on each wall with all the information pertaining to that specific wall (and not the entire floor), (2) standardization by developing a format with the expected content in each PDF package so that the development of the packages could be done by a third party instead of an assigned superintendent or project engineer.

Visually Communicating Expectations and Outcomes

The team adopted visual management to communicate the expectations of delivered work and whether the work conformed with the acceptance criteria defined. For instance, when preparing for city inspections in the framing stage, the drywall contractor spray-painted the fasteners on the framing bottom track (Figure 4). When the city inspector walked the site, he quickly verified that fasteners were installed, conforming with the agreed acceptance criteria. The inspector appreciated the drywall team doing this because it helped them to conduct inspections faster.

> *"The [city] inspector asked me to paint all the [fasteners on the bottom track] so that he didn't have to spend time looking where they are; he just wanted to walk and quickly see where they were installed." – Drywall Foreman*

Figure 3: Photo Included in PDF Package Showing Pipe Location with Respect to Corner

Figure 4: Fasteners Ready and Spray-Painted Green for Inspection

DISCUSSION

The system we introduced in this paper, the BBQS, is one way to approach BBQ from a systems perspective. While building the BBQS, we identified a set of features to facilitate BBQ understanding and adoption. Because every project team is unique, practitioners may apply some of the BBQS features more than others and to a different extent. For instance, in our case study of a project that successfully delivered quality expectations, we analyzed how the behaviors feature was observed by the participants involved and what opportunities for improvement can be explored further. In terms of active learning, although the interviewees reported doing well in learning from issues and experimentation, the learning process itself could have been improved. Participants acknowledged that some defects were repeated because it had 'slipped my mind' to develop countermeasures. The team could have documented the lessons learned more systematically and reviewed those lessons before moving to the next work area.

The BBQS features we presented are intertwined. For instance, the processes developed by the team supported the behaviors they displayed and vice versa. For example, when using the QR codes, the team enabled every trade to do their quality control and encouraged them to raise any issues while checking their work. Also, trade damage discussions fostered discipline in documenting damage, and created a fair and transparent environment that contributed to team collaboration and an increase in active caring for the work of others, ergo minimizing damage. The BBQS features of a quality system based on Lean foundations are meant to be further refined and augmented.

CONCLUSIONS

Few publications have addressed the role of the human factor from a behavioral perspective of those participants involved in defining quality expectations and meeting them. Some emphasized the need to develop a more behavior-based approach to managing quality, proposing BBQ for construction projects. Acknowledging that behaviors matter for the delivery of quality expectations, this paper answered the question: How do we take the main idea of BBQ and make it actionable so that project teams can implement it? This paper contributes to the literature by proposing a more systemic thinking about BBQ and presenting the features of a system, the BBQS, that supports such thinking.

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ASSESSING QUALITY PERFORMANCE OUTCOMES & THE RELATIONSHIP WITH RFI AND PCI PROCESSES: A GENERAL CONTRACTOR CASE STUDY

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ABSTRACT

This paper is the third in the series, taking a cross-discipline view of project performance to investigate and understand the potential correlation between system inputs and outputs. In the 2021 paper "The Impact of Implementing a System Approach to Quality: A General Contractor Case Study," the authors compared project performance outcomes and team cultural assessments for 11 projects that had implemented a Systems Approach to Quality (SAQ), the Intervention group, against a similar set of projects that had implemented a compliance-based approach to quality, the Control group. This paper continues to investigate the project performance outputs for these two groups and specifically looks at the Request for Information (RFI) and Potential Change Item (PCI) workflows. This case study considers if RFI and PCI metrics can be used to determine if better quality design contributed to better performance outcomes. Then it considers how RFI and PCI processes relate to SAQ implementation. The authors' findings suggest that applying SAQ resulted in project teams documenting RFIs sooner in the project lifecycle and experiencing faster closure rates compared to the Control group.

KEYWORDS

Systems Approach to Quality (SAQ), Request for Information (RFI), Potential Change Item (PCI), Change Order (CO), design quality, performance outcomes

INTRODUCTION

THE REWORK PROBLEM & DESIGN QUALITY

Rework is a known problem in the Construction Industry. This General Contractor (GC), with a current US $5.9B revenue, headquartered in California and working throughout the US, Europe, and Singapore, experienced unpredictable results when delivering their final product. Sometimes the GC delivered work to meet customer expectations; sometimes, the GC achieved zero defects at substantial completion; and other times, the GC spent a lot of time and money

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to close out open issues. Even when the GC met plan and specification requirements, sometimes the owner would say, “That was not what I was expecting. Tear it out and re-do it.” (Spencley et al., 2018).

Receiving accurate information promptly to plan and build the work has long been discussed as essential to preventing rework and growth of project costs (Hughes and Zack 2012). Design quality and preventing design errors and omissions are vital as they directly influence the overall performance of construction projects (Alarcon and Mardones 1998). A study performed on nine industrial projects found that design deviations averaged 78% of the total count of deviations. These were further sub-categorized, and “design changes for improvement (DCI) caused, on the average, the greatest number of deviations, 13.3%, followed by design changes in process (DCP), 10.9%, and design changes initiated by the owner (DCO), 9.9%, while 13.2% of the total number of deviations were classified as design changes of unknown origin (DCU)” (Buratie et al., 1992). Furthermore, design changes averaged 79% of the total costs for all changes and 9.5% of the entire project costs (Buratie et al., 1992).

Hughes and Zack (2013) attribute this lack of information to a shift away from a master builder that designed, planned, and executed the work. While project designs have become more technically complex, designs and building duration times have become condensed, leading to missing information on the design documents (Dougherty et al., 2012). Thus, the Request for Information (RFI) process became a tool for the construction industry to ask designers clarifying questions about the intent of the design and receive the information necessary to build what was expected. If impacts are associated with the RFI response provided, the general contractor submits the proposed scope, costs, and schedule impacts in the Change Order (CO) process (Dougherty et al., 2012).

Measuring the outputs of the RFI and CO processes has become standard metrics to evaluate how a project is performing. First, RFIs have been used to measure design quality (Tilley et al., 1997), a leading indicator of how projects will perform. In the ASCE study “Defining the Success Status of Construction Projects Based on Quantitative Performance Metrics Thresholds,” RFIs and Change Orders quantities were used to differentiate between successful and non-successful projects (Aboseif et al., 2022). Similarly, this GC uses the volume of RFIs a project experiences to signify if projects have unanticipated changes and potentially could not meet the existing contractual requirements. If the count of RFIs for a project increases above the weekly average the project has been experiencing, this is considered a warning that the design quality does not reflect the information the GC needs to build. However, one challenge with this approach is that these comparisons were all made without distinguishing between successful and unsuccessful projects (Aboseif et al., 2022).

THE RESEARCH QUESTION

In previous research, the authors identified that projects implementing a Systems Approach to Quality (SAQ) achieved better performance metrics across quality, safety, cost, change management, schedule, and collaborative culture, versus a similar set of projects that implemented an industry standard, compliance-based approach to quality, the Control group, (Gordon et al. 2021a). Through this current research, the authors continued to investigate the project workflows for these two groups and looked at the Request for Information (RFI) and Potential Change Item (PCI) workflows, which is a required and leading step to issuing a formal Change Order (CO) for this GC. The authors endeavoured to understand the following:

- Can the RFI and PCI process metrics collected by this GC support assessing if design quality contributed to the Intervention group achieving better project performance outcomes and more collaborative cultures?

- Are there discernible differences in outputs for standard communication workflows, the Request for Information (RFI) process, and the Potential Change Issue (PCI) process through the project lifecycles?
- Can the outputs of these standard communication workflows be leading indicators of project performance and cultural outcomes of projects?

The hypothesis: SAQ projects which created systems to build from knowledge and information, understand and align objective expectations for deliverables, including design packages, would have fewer RFIs and less towards the end of the project as many details were worked out ahead of time. Also, the categorization of the change would help identify those associated with design quality. When the change occurred would be an indicator of how SAQ influenced information flow. The authors also planned to review how the groups documented schedule information in the PCIs to understand how implementing SAQ influenced teams' internal planning and communication. The authors sought to determine if project RFI workflows would provide evidence about project design quality.

This study is important as it assesses standard process outcomes between projects that implemented SAQ and experienced better performance outcomes versus a Control group. The findings of this study can help leaders create project performance process thresholds and identify when projects "are in trouble" and need help, such as a different strategy or support.

THEORETICAL FRAMEWORK

SYSTEMS APPROACH TO QUALITY (SAQ)

Bertelsen described construction projects not as linear and ordered but as complex and dynamic systems (Bertelsen 2003a; Bertelsen 2003b). Like Bertelsen, this GC recognized projects are complex and dynamic and desired reliable, consistent, and predictable outcomes for quality on their projects (Spencley et al., 2108). To solve the rework problem this GC faced, they developed a Systems Approach to Quality (SAQ) (Gordon et al., 2021a). Foundational to SAQ are the principles: identifying Points of Release (PoR), when work is released to the next phase, building from knowledge and information, understanding expectations, and Distinguishing Features of Work (DFOW) from each stakeholder's perspective, aligning expectations to measurable acceptance criteria for the work, tracking and visualizing leading indicators, and performing causal analysis when evaluated work does not meet the expectations of the deliverable (Gordon et al. 2021a). These principles are applied to the project strategy and across the projects' many workstreams of safety, quality, cost, planning, and change management to deliver the expected deliverable at each PoR.

PREVIOUS RESEARCH

This paper is the third in a series to assess projects that implemented SAQ, the Intervention group, versus a similar set of projects that implemented an industry standard, compliance-based approach to quality, the Control group. The first paper measured project performance outcomes between the two groups for cost, schedule, change management, safety, quality, and cultural outcomes using Quinn's Competing Values Framework (CVF) and found that those that implemented SAQ had better performance outcomes more aligned with company objectives (Gordon et al. 2021a). In follow-up research, Gordon et al., 2022 reviewed contract date relative to project duration and studied staffing and resourcing profiles between the project groups to understand if different inputs contributed to better performance outcomes (Gordon et al. 2022).

Through this previous research, the following was reported:

- "Cost: The median value of cost growth for the Intervention group was 5% and 9% for the Control group. The median value of fee gain for the Intervention group was 4% and -35% for the Control group.
- Schedule: The median value of schedule growth at mobilization for the Intervention group was 11% and 18% for the Control growth.
- Change Management: The median value of contract changes was 5% for the Intervention group and 13% for the Control group.
- Safety: The median value of incidents per $100M for the Intervention group is 1.5 and 1.9 for the Control group.
- Quality: The median value of claims as a percentage of contract cost for the Intervention group was 0.14% and 0.87% for the Control group.
- Project cultures: Using Quinn's Competing Values Framework (CVF), the Intervention group reported more collaborative cultures" (Gordon et al., 2021a).
- Signing the contract, the Guaranteed Maximum Price (GMP) as a percent of project duration: The median value for the Intervention group was .09% and 19% for the Control group" (Gordon et al., 2022).
- The median value for time coded to VDC resources was approximately 3x more for the Intervention projects (Gordon et al., 2022).
- The Intervention projects also outsourced more project management work (Gordon et al., 2022).

LITERATURE REVIEW

The RFI and CO processes are standard processes in the construction industry and have been used to assess drawing quality and communication of construction projects. Tilley et al., 1997 concluded that evaluating the RFI workflow with the drawing register can indicate design and documentation quality and status of project performance and analyzing the number of RFIs relative to contract value and project schedule, and response times can be used to assess the severity of the issues (Tilley et al., 1997). Similarly, a 2021 Construction Industry Institute study stated: "'RFI/$M' is a shorthand metric for project communication and design quality. In general, more RFIs are a 'bad sign.'" Furthermore, several studies review project RFI metrics for the projects investigated (Tilley et al., 1997; Hughes et al., 2013; Construction Industry Institute, 2021). The Navigant Construct Forum studied a data set of 1,362 projects from all over the globe between 2001 and 2012. They documented the following:

- There were 1,083,807 RFIs submitted on these projects, averaging 796 RFIs per project.
- Average number of RFIs per million dollar is 9.9 for all projects.
- First response was calculated at 6.4 days and a median response time of 9.7 days (Dougherty et al., 2012).

Aboseif et al., 2022 published criteria for success metrics for communication by using quantitative performance data from 96 projects:

- RFI per $million less than or equal to 8.6
- RFI processing time less than or equal to 7 calendar days
- Fewer than .39 change orders per $million

Although the RFI process has waste and inefficiencies (Tilley et al., 1997, Alarcon and Mardones, 1998; Uusitalo et al., 2020), the RFI process is a standard communication process.

In the literature review, the authors realized there is a gap in investigating what the RFI and PCI flow looks like through the project lifecycle.

RESEARCH METHODOLOGY

METHOD

To investigate their questions, the authors used the same project data set from the 2021 and 2022 case studies (Gordon et al., 2021a; Gordon et al., 2022). Eleven projects that implemented SAQ and were within 90% of completion by January 2022 were chosen as part of the Intervention group. For each SAQ project, a project of similar contract size, geographical location, and core market, when available, that did not implement SAQ was chosen for the Control group. The authors again applied the design thinking and systems thinking concepts and tools from the Center for Innovation in the Design & Construction Industry's (CIDCI) online innovation lab (CIDCI 2022) (Gordon et al., 2022). The process involved six steps.

First, the authors further explored the problem statement using the "web of abstraction" tool to frame and re-frame the question. Next, the authors spoke with experts in operations, data analytics, project controls, and scheduling. The discussions revealed that the organization had dashboards to understand the number of RFIs project teams were experiencing each week compared to the project's current average. Additionally, one operations expert analyzed RFI-to-PCI ratios to help project teams forecast the amount of PCI work based on RFIs produced. Through the enterprise Operations Data model tool, the authors could observe the counts of RFIs, and PCIs related to data points, like the reason for and the type of assembly associated with the RFI and PCI. The scheduling subject matter expert identified, including the proposed time of work in the PCIs and whether the work can be done concurrently or will extend the critical path, is crucial information needed to forecast more reliable plans.

The third step involved reviewing the collected data and identifying the information needed to investigate the questions. During the study period, RFI and PCI information was collected in a centralized project management software platform. When project teams seek clarification or an interpretation of the contract drawings, an RFI is initiated in the software when the subject, created date, from, and to fields are entered. When additional details such as discipline, agency review required, questions, suggestions, potential schedule and cost, and relevant attachments are added, the RFI is submitted via the company's project management software to the appropriate project stakeholder and enters pending status. If the stakeholder's response requires additional time and money above the contracted baseline work, a Potential Change Item (PCI) with scope, cost, and schedule impacts is submitted via the project management system for owner approval. Once the required fields of Type of PCI (Owner, Category Transfer, or Original Budget Change), Description, Status, and Date Initiated are entered, the PCI is created. When the owner approves the PCI, a formal Owner Change Order (OCO) is submitted.

Next, the authors mapped the available information to the questions and brainstormed how to visualize and compare the groups' data. The authors planned to visualize and analyze the type of RFI categorization through the project lifecycle. However, since RFI categorization was an optional field, this data was not available for many of the projects. Similarly, the amount of time projected for the work was an optional PCI field, and this information was not always available. Thus, the authors focused on looking at the counts of RFIs and the value and count of PCI data through the project lifecycle to determine design quality. The authors developed visuals of the data and then analyzed it.

DATA COLLECTION

From the company's enterprise project management software platform for both the RFI and PCI workflows, the following data was exported for each RFI and PCI: date created, date information is requested, date submitted to project stakeholder, date response submitted, and date closed.

The RFI and PCI data were compiled and reviewed for each project by two different project duration views. The first view compiled the RFI and PCI data for 1) the time before signing the GMP and 2) after signing the GMP. In the previous study, the authors found a significant difference between when the Intervention and Control groups signed the GMP, .09% and 19% of project duration between mobilization and substantial completion, respectively (Gordon et al., 2022). Thus, the authors investigated if there were differences in the RFI and PCI patterns for these durations. Secondly, the authors normalized the information by standard project milestones: actual mobilization date and substantial completion (Gordon et al., 2022). The authors looked at the time before mobilization and called this period the pre-game quarter. Then for each project, the authors compiled standard durations for the project lifecycle by taking the time between the actual mobilization date and substantial completion date and dividing that into four equal durations that included: mobilization date to 25%, 25% to 50%, 50% to 75%, and 75% to substantial completion. Data for each project was reviewed in these five quarters and aggregated into each group, to compare group trends.

For RFIs and PCIs, the following metrics were calculated for each project and then for each group, Intervention, and Control by the two durations: 1) Total count, 2) percent of the total count, 3) average closure rate, 4) RFI/PCI per million 5) RFI per 1000 hours of staffing.

Table 2: Performance Metrics and Units of Measurements

Metric	Formula
RFIs/PCIs per $million	$\frac{Total\ Count\ of\ RFIs/PCIs * 1{,}000{,}0000}{Contract\ Value}$
RFIs per 1,000 hours of GC Hours	$\frac{Total\ Count\ of\ RFIs * 1{,}000}{GC\ Hours}$

DATA FINDINGS

The following RFI and PCI performance metrics were calculated: 1) RFIs per million were 5.2 and 6.4, respectively, for the Intervention and Control groups; 2) RFIS per 1,000 hours of GC hours were calculated as 9.4 for the Intervention group and 11.8 for the Control; 3) PCIs per million were 4.1 and 5.6, respectively for the Intervention and Control groups.

Figure 1 compares the total GC hours for the Intervention group versus the Control group for each quarter of the project. The y-axis represents the count of staff hours reported in the GC's weekly billing submissions, and the x-axis represents the entire project lifecycle in the five quarters. The x-axis is standard for all the following graphs.

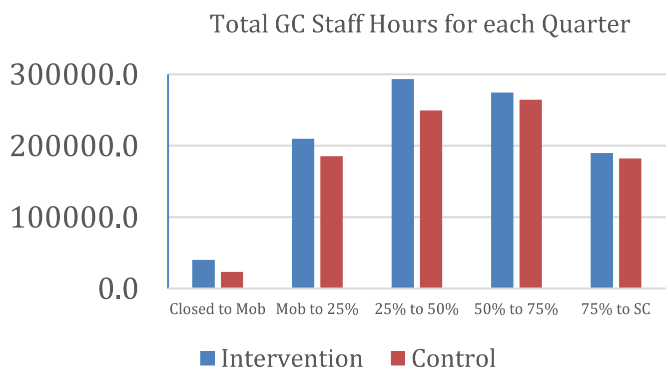


Figure 1: Count of total GC hours

Figure 1 shows that overall, the Intervention group reported 12% more staff hours than the Control group. In the pre-game quarter, before being on-site, the Intervention group had nearly double the staff hours as the Control. Box and whisker charts also revealed that the Intervention group had more variability in the count of hours staffed for their group of projects.

The graphs in Figure 2 show two views of the total RFI counts for the Intervention and Control groups. The left chart summarizes the count of RFIs for each duration in the project lifecycle, and the right graph plots the median values of the counts as a percentage of total counts for each duration.

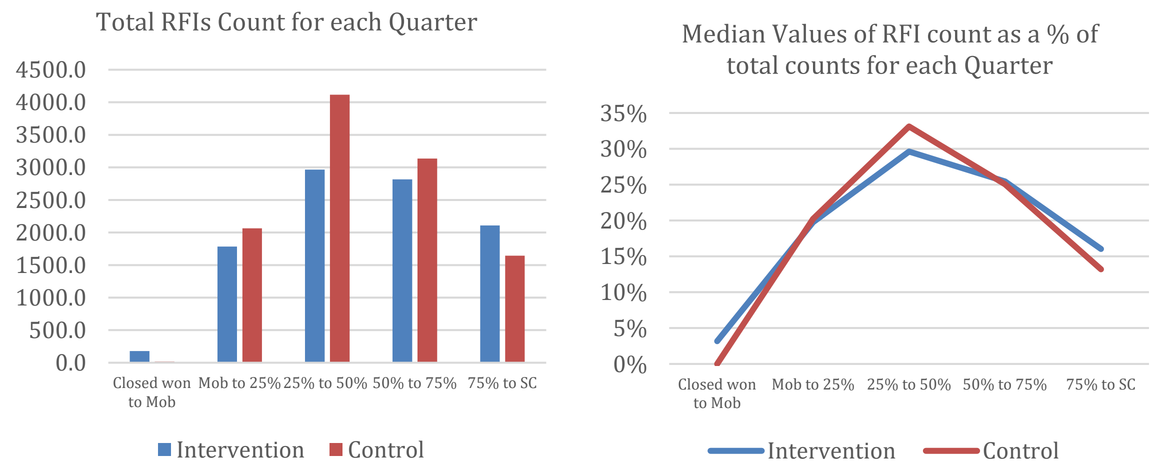


Figure 2: Total RFI counts and median value RFI count as a percentage of total counts.

Overall, the Control group submitted 10% more RFIs than the Intervention group. One significant difference is that the Intervention group reported 9.5x more RFIs than the Control projects before mobilization. In the three quarters after mobilization, the Control group had more RFIs. In the last quarter, the Intervention group submitted 25% more RFIs. For the graph on the right, the median values are similar for the percentage of total counts. The box and whisker analysis demonstrates that both groups had similar ranges and much variability for the four quarters after mobilization.

Figure 3 provides comparable PCI visualizations. The left graph summarizes the count of approved PCIs, and the right chart summarizes the median value of approved PCIs as a percentage of total approved counts for each of the five time periods.

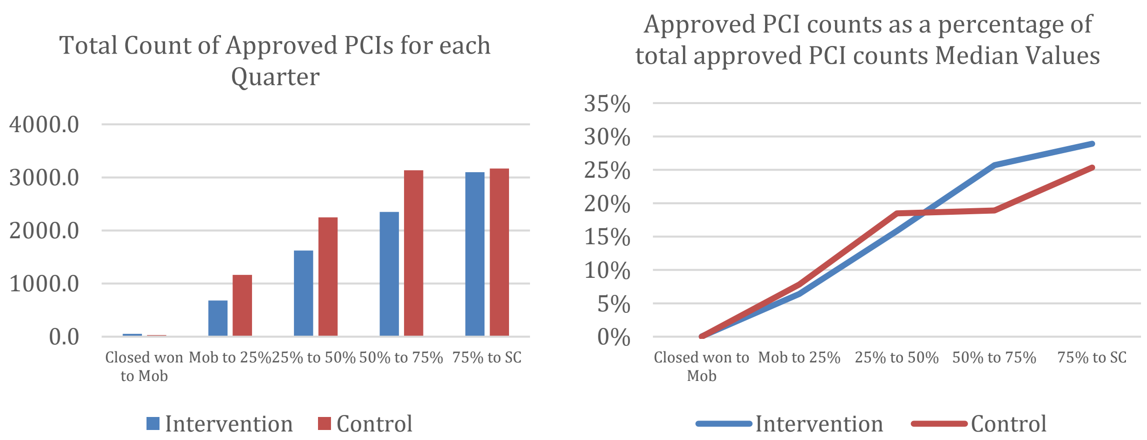


Figure 3: Count of approved PCIs and the median value of approved PCIs as a percentage of total approved PCI counts.

The left graph of Figure 3 shows that the Control group had more approved PCIs throughout the project lifecycle. This is expected as the previous research documented 8% more change than the Intervention group as a percentage of the overall contract value. The graph on the right shows that the Intervention group had more variability and a range of PCIs approved in the last two time periods of the project.

The RFI closure rate was calculated by subtracting the RFI date created from the date closed. Then, the average closure rate was found for each project in each duration, and the median value for each group, Intervention vs. the Control, was plotted as shown in Figure 4. The y-axis represents days in time, and the x-axis represents the normalized periods.

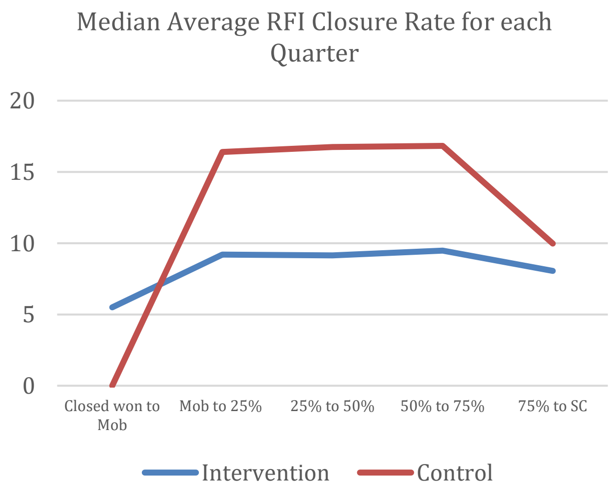
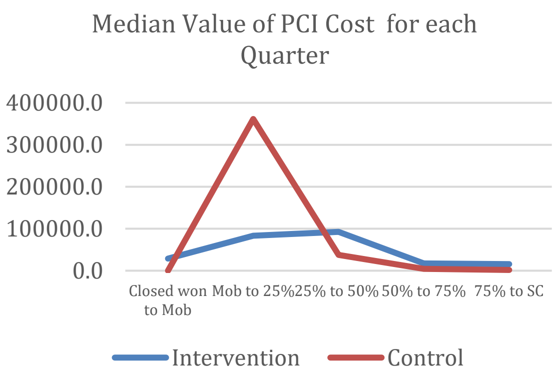


Figure 4: Median values for the average RFIs closure rate for the Intervention Group vs. Control group for the normalized periods.

From mobilization to 75% of the project duration after mobilization, the Control group's median average closure rate is 16 days. This is twice the Intervention group's median value, which was an 8-day closure rate during this period.

Figure 5, the left graph, shows the median PCI cost for each group during each of the five quarters. Previous research showed that the Control group experienced more change as a percentage of the total cost. For the Control group, the median value for PCI cost spikes after mobilization, and the box and whisker charts reveal that the second quarter experiences the most variability. For the Intervention group, the box and whisker charts show that the pre-game quarter, the quarter before mobilization, experiences the most variability in PCI costs. Figure 5, the right graph, shows the average PCI closure rate for each quarter. While the Intervention group's median value for closure rate steadily increases until the quarter before substantial completion, the median value for closure rate for the Control group is highest in 25% to 50% of the project after the GMP was signed.



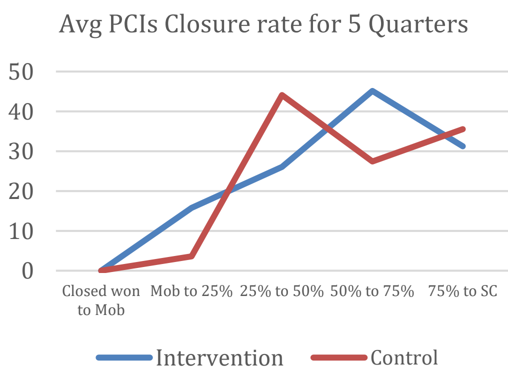


Figure 5: Plot of median values of the PCI cost for five quarters.

LIMITATIONS OF THE DATA

Data limitations include 1) that this is only a case study of 22 projects; 2) the projects were either classified as having implemented SAQ based on conversations with the project team and their presentations at the organization's Monday Quality Calls forum (Gordon et al., 2021a) or not implemented; 3) Total counts of RFIs were based on RFIs with a created date and not a submitted date. The authors found a small percentage of RFIs that were created but not submitted; 4) When the contract required the project team to use a different project management software system, fields were used that coincided with the data collected in the GC's enterprise system; 5) The analysis does not distinguish between project delivery system; 6) The RFI and PCI analysis does not differentiate between the type of change requested – whether it was a clarification, error or omissions, an improvement, or change directive; 7) Category transfers were included as PCI counts.

DISCUSSION

MEANING

The Intervention group, which consisted of projects that implemented SAQ, submitted more RFIs before mobilization. This suggests that implementing SAQ and formal documentation of early and essential design decisions could contribute to signing the contract sooner, which allows the GC to focus on the execution of the work and better performance outcomes. Both groups had roughly the same median values of RFIs created before and after GMP, approximately 20% and 80%, respectively. However, the Intervention group's median value for signing the GMP was within 1% of mobilization, 18% sooner than the Control group. This suggests that the RFI and PCI work needed by mobilization for a project to have reliable outcomes can be determined and used to measure how projects are trending. The Intervention group, with twice as much stuff as the Control, also asked more questions earlier in the project lifecycle, suggesting implementing SAQ and staffing, and not design quality was a key to contributing to better performance outcomes.

The median value for the closure rate of RFIs for the Intervention group after mobilization for three quarters, while the project was in construction was 8 days. The Control group's median value for this same time was 16 days. The Intervention group received information in the project earlier and faster than the Control. This experience could contribute to the Intervention group's results on Quinn's CVF, where they ranked higher on collaboration than the Control group Control that more collaboration would lead to even more success (Gordon et al., 2021a).

Also, the timeframe when projects experienced Potential Change Items (PCIs) differed. The Intervention group experienced a lot more variability in the pre-game quarter before mobilization, while the Control group experienced more variability in the quarter following mobilization. This suggests that the Intervention group, applying the principles of SAQ, was better able to adapt and communicate and resolve changes with stakeholders earlier in the project and agree to the GMP sooner. Also, the large PCI numbers the Control group forecasted after mobilization could have contributed to the delays in signing the GMP.

The data also showed that the Control group had created 54% more total PCIs. The Control created nearly 3x as many PCIs as the Intervention group in quarter three, 50%-75% between mobilization and substantial completion. However, only a third of those created PCIs turned to approved status. The elimination or rejection of created PCIs could account for the Control group's lower average closure rate compared to the Intervention group during this period. This also demonstrates the additional workload the Control group was experiencing with fewer staff.

IMPLICATIONS

This study demonstrates how normalizing views of cross-discipline information in relation to project lifecycle can provide more insight into leading indicators or early system outputs that could alert the GC's organization to how a project's performance is trending and when intervention is needed. The work is also important as it demonstrates how GCs can leverage their enterprise data to intermediate benchmark project deliverable outputs that produce known outcomes.

CONCLUSION

KNOWLEDGE GAINED BY PARTICIPANTS, AND VALUE FOR PRACTITIONERS

The authors learned from this case study that RFIs documented before mobilization can be a leading indicator of project performance success and collaborative cultures. The GMP will also likely be signed earlier in the project lifecycle. Additionally, more PCIs in the pre-game quarter is another leading indicator of project success and suggests that the organization look at PCI value in relation to the mobilization date to understand how projects are trending. The RFI closure rate significantly differed between the groups suggesting this is a critical lagging indicator demonstrating that a project is experiencing issues.

When the authors compared their case study findings for RFIs per million and closure rates against reported industry metrics, they found some differences. Hughes et al., 2013 research indicated that 9.9 RFIs per million is typical for projects, and Absoeif et al., 2022 stated that 8.6 RFIs per million was a successful project threshold. In this case study, both Intervention and Control groups had median values below that criteria, 5.2 and 6.4, respectively. This finding highlighted for the authors the importance of performing these studies and broadening them with their organization's data to understand representative benchmarks.

Finally, normalizing views of the organizational data to standard project milestones and taking a cross-disciplinary view of the data is essential for a more holistic understanding of what projects are experiencing. From this work, the following are early indicators for a successful project: the percent of total estimated staffing hours spent in planning before mobilization, the number of RFIs based on estimated project value that should be submitted before mobilization, and the planned duration for GMP approval needs to be by mobilization.

FURTHER RESEARCH

While it is generally accepted that lower RFI counts equate to better quality design (Construction Industry Institute, 2021), this would suggest the Intervention group had more complete, clear, and concise information to build from. However, more investigation is needed to answer this question. In implementing SAQ, the teams' focus on understanding and aligning expectations for processes of engagement, communication, and for information needed to build could have contributed to fewer RFIs as well. This project group also documented 3x more VDC resources, likely facilitating increased communication and understanding. A social network analysis of the project groups could also be performed to analyze if there are patterns for how stakeholder knowledge intersects with the social network to create a better-quality design. Additionally, the type of change requested in the RFI should be analyzed to categorize the reasons for the change and assess design quality. The authors would also like to investigate the types of PCI changes each project group is experiencing and how proposed schedule information is documented to understand if any internal communication and planning patterns exist that could inform project performance trends.

For further research, the authors also aspire to explore the interactions and workflows for understanding and aligning stakeholder wants, needs, and project expectations and how the workflows and processes differ between the groups. The authors want to investigate how these project system outputs are visible in the organization's enterprise system data. This knowledge can be used to determine additional leading indicators of project performance trends.

Furthermore, the authors suggest broadening this study and previous papers from 2021 and 2022 to apply multivariable statistics to create statistical thresholds for project performance outcomes, cultural outcomes, staffing and resourcing profiles, and standard process outputs. For benchmarking, the authors would like to explore these views based on project type, customer accounts, design partners, project delivery system, and other project characteristics that would inform the GC's execution strategy.

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OCCUPATIONAL STRESS IN CONSTRUCTION: FOSTERING AN IGLC RESEARCH AGENDA

Saad Sarhan[1], Stephen Pretlove[2], Alan Mossman[3], and Mohammed Z.E.B Elshafie[4]

ABSTRACT

Globally mental health is a serious concern, particularly in construction. According to the Health and Safety Executive (HSE, 2021), stress, anxiety, and depression are the second biggest cause of work-related ill health in the UK construction industry. Occupational stress and mental health issues should, therefore, be treated with the same level of significance as physical health and safety risks in construction. To the authors’ knowledge, there are very few, if any, published empirical IGLC papers that have explicitly focused on this concern. This study was conducted using case-study interviews and a focus group with industry experts, to explore and promote the concept of ‘occupational stress’ in construction. The study provides novel contributions to knowledge, which include: identifying seven main sources of stress (i.e. stressor) in UK construction projects, revealing ‘workflow interruptions’ as a prevalent and severe source of stress in construction, shedding some empirical light on the inadequacies of the critical path method, and generating new questions and proposals to pave the way towards a future IGLC research agenda for tackling occupational stress and mental health issues in construction.

KEYWORDS

Lean construction, stress, mental health, flow, waste

INTRODUCTION

Occupational stress is increasingly becoming an issue of major concern all over the world. In the UK, for instance, it is estimated that stress-related illness costs the British industry £5 billion each year, with the Health and Safety Executive (HSE) calculating that stress, depression or anxiety account for 44% of all work-related ill health cases, and more than half of all sick days in an average year. The COVID-19 pandemic, the Russia-Ukraine war and the resulting global economic recession have further compounded these issues, by creating additional unprecedented social and economic pressures on the mental health and well-being of many people, particularly those working in construction.

In the US, the 2021 National Veteran Suicide Prevention Annual Report shows the [military] veteran suicide rate was 31.6 per 100,000 veterans in 2019. The adjusted suicide rate for the same year for all US adults is 16.8 per 100,000. The data shows the construction industry suicide rate is 53.2 per 100,000. Does that mean it is *"easier on a person’s mental state to be*

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asked to prepare for and propagate war than to work in construction?" (Winningham 2022). It doesn't have to be this way.

Stress in itself is not an illness, but it can make people ill. HSE (2021) defines work-related stress as "*the adverse reaction people have to excessive pressure or other types of demand placed on them*". Stress affects employees, their families and colleagues, by making their physical and psychological condition worse. This in turn affects employers who have to deal with increased sickness absence, lost productivity, human error leading to re-work, increased accidents, replacement of staff and poor performance within their organisations. Figure 1 illustrates how the level of stress can impact on the individual's performance at work.

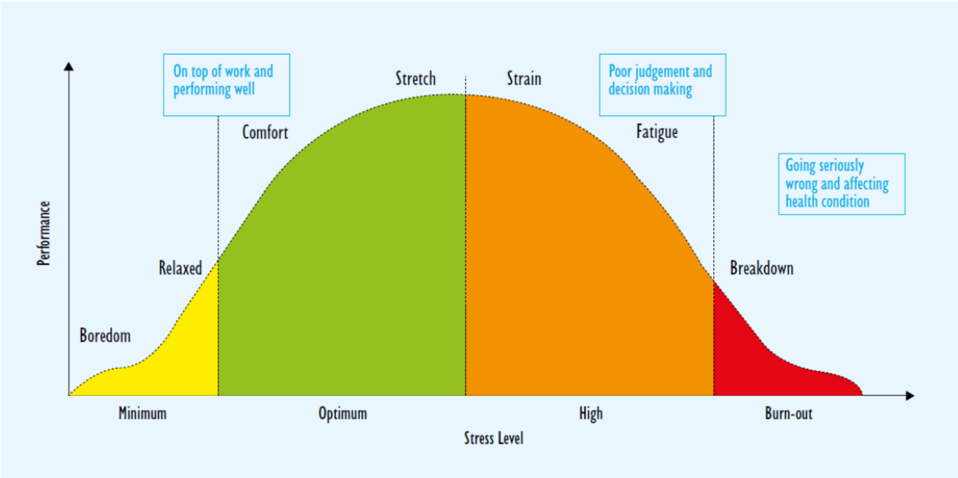

Figure 1: The Influence of Stress on the Individual's Work Performance
[Chart produced by Mates in Mind; cited in CIOB (2020)]

Despite the relatively low levels of 'reported' work-related stress in the construction sector, when compared to other industries, there is anecdotal evidence that occupational stress and mental health are increasingly becoming critical issues of concern within the sector (CIOB, 2006; HSE, 2007; CIOB, 2020). Several empirical studies have identified work-related stress as one of the root causes of unsafe behaviours in construction (for example, see Seo et al., 2015; Leung et al., 2016; Wu et al., 2018). Other major social problems such as high absenteeism, presenteeism, alcoholism, drug abuse and suicide have also become increasingly reported as consequent to occupational stress in construction. The CIOB's (2020) report described mental ill-health as a silent *crisis* within the construction industry, with males three times more likely to commit suicide than those in other sectors.

Why are People in Construction Particularly at risk?

People working in construction are particularly vulnerable to suffering from mental health issues (Oswald et al., 2019). There are various systemic and inherited problems in construction (Sarhan *et al*., 2017), such as its risk-averse and blaming culture, cut-throat price competition, the traditional macho culture, long and fragmented supply chains, late payments, slim profit margins, tight deadlines and challenging working conditions, skills shortage and job insecurities, all of which contribute towards increasing stress and anxiety in construction.

Most of the workforce in construction are self-employed, and thus getting regular and reliable work can be very challenging for them. This job insecurity can contribute significantly to their poor mental health. In addition, these casual or self-employed workers may not have or be aware of any mechanism for reporting their work-related stress and mental health issues. Furthermore, the majority of workers in construction are employed by small and medium enterprises (SMEs), and it can be difficult for smaller companies, due to their limited budget and resource constraints, to put the right arrangements in place for supporting the mental health and wellbeing of their employees.

RESEARCH GAP AND OBJECTIVES

Many research studies have focused on investigating physical health problems and safety performance in construction. However, much less research has studied mental health issues affecting construction practitioners (Oswald et al., 2019). In addition, efforts in both academic and practitioner communities in construction focus mainly on managing occupational stress, as opposed to preventing or reducing its occurrence. Many studies on stress in construction have set out to identify its causes and effects at individual, task and organisational levels. Very few, if any studies, have sought to investigate the sources of stress (i.e. stressors) at a project or supply-chain level.

Lean Construction (LC) has shown to be effective in managing H&S risks in construction through integrating safety into production planning and control processes (Saurin et al., 2002; Sacks et al., 2005). Various LC tools and techniques have been used to improve safety performance in construction, including the use of the Last Planner® System, 5Ss program, BIM, visual management, and off-site construction. The idea is that an early focus on physical safety performance will also help in improving productivity, process transparency and minimising time and cost wastes resulting from accidents on construction projects. Guided by the two core lean principles of respect for people and continuous improvement, a limited but increasing number of IGLC studies have been used to promote the importance of considering psychological safety in construction.

Interestingly, there are only six conference papers within the IGLC repository (from 1996-2022) that explicitly focused on this critical topic of mental health in construction (see Table 1). This study, therefore, hopes to contribute to this topic by presenting the findings of a focus-group with UK industry experts. The ultimate aims of this study are to:

- Identify the main sources of occupational stress in UK construction projects,
- Propose strategies for preventing or reducing stress in construction projects
- Promote an IGLC research agenda for addressing mental health issues in construction

Table 1: An identification of relevant IGLC papers on mental health issues

Author (Year)	Paper title	Method
Filho et al. (2018)	'Respect for people's well-being: meditation for construction workers'	Case-Study
Oswald et al. (2019)	'Mental Health in the Construction Industry: A Rapid Review'	Literature Review
Muñoz et al. (2019)	'Team Health: A Measured Approach to Collective Learning'	Action learning
Gomez et al. (2019)	'An Active Care Approach Through Psychological Safety in Construction Projects'	Mixed methods
Gomez et al. (2020)	'Lean, Psychological Safety, and Behavior-Based Quality: A Focus on People and Value Delivery'	Mixed methods
Padia et al. (2022)	'Employee's Mental Wellbeing with Reference to IEQ and Managerial Environment in Office Spaces'	Mixed methods

RESEARCH METHOD

This study forms part of a larger research study that was funded by a UK charitable trust to develop supply-chain management (SCM) strategies for improving stress management and productivity in construction. The study adopted a qualitative multi-methods research approach, comprising a qualitative systematic literature review, case study, and a focus group. Empirical data were collected from a UK case-study through site observations and iterative semi-structured interviews. The case-study was selected because it was a live project which allowed the first author of this study to conduct multiple visits, observations and iterative conversations with the site team. It was also delivered by one of the most recognised main contractors in the UK, which was an essential criterion, to allow the study to capture examples of best practices in relation to H&S and SCM. The authors also had direct access to the client's project management team. The main features of the case-study project are as follows:

- Higher Education building in the UK
- Design and Build project procurement method using two-stage tendering
- Contract value ~£30 Million, duration was 2 years
- NEC 4 contract, BIM, and prefabrication techniques were used.

In total, 19 in-depth interviews were conducted as part of the case-study with a sample of construction workers at different levels (e.g. forepersons, supervisors, site workers, project managers, site managers) and representing the various parties of the project supply-chain (client, main contractor, and subcontractors). The data collected from the case study interviews and site observations were analysed using NVivo software, following Strauss and Corbin's (1998) formal procedures for data coding and analysis. A focus group was then used to evaluate the findings of the case-study (i.e. the themes and conclusions that emerged from the qualitative data analysis phase). This paper focusses on the findings of the focus-group.

FOCUS GROUP: METHODS AND TOOLS USED

This focus group was conducted to evaluate the findings of the case-study, collect feedback from wider industry stakeholders, and assess the extent to which its findings could be generalised. Focus group participants were selected to ensure that all participants had broad and significant experience in the construction industry (see Table 2).

Table 2: Focus Group Sample

No.	Job title of participants of the focus group	Years of Experience
P1	Consultant and Fellow Member of the Institute of Civil Engineers (FICE)	30+
P2	National Civil Engineering Director at the Civil Engineering Contractors Association	30+
P3	Professor of Sustainable Construction	30+
P4	Professor of Lean Project Management	30+
P5	Operational Change Manager at a Leading Consultancy Company	20-30
P6	Engineering Manager at a British County Council	20-30
P7	Business Development Manager at a Subcontractor	20-30
P8	Business Development Manager at a Charitable Trust	10-20
P9	Growth Development Manager at a Leading UK Charity Organisation	10-20
P10	Group Director of H&S at a Main Contractor	10-20
P11	Production and Performance Manager at a Global Consulting, Engineering and Construction Management Company	10-20
P12	Health & Safety Programme Manager at a Leading Global Construction Company	10-20

The focus group was conducted online and lasted for an hour and a half. Two of the authors of this study started by delivering a 20-minute presentation to summarise the findings of the case-study. They then introduced an interactive survey using a web-based response system named Poll Everywhere. This application allows the participants to anonymously answer questions. The results are, however, displayed and updated live for all to see. The whole session was video recorded (following the agreement of all the participants) to capture feedback, interactions, and comments during the discussion of the results.

RESEARCH FINDINGS AND ANALYSIS

The following sections summarise the main findings of the study.

THE MAIN SOURCES OF STRESS IN CONSTRUCTION PROJECTS

Based on the findings of the case study (listed in Figure 2 below), the focus group participants were asked to select the stressors that they believe are ‘prevalent’ in construction projects. ‘Work demands’ (i.e. work load, and unrealistic project budgets and demands) and ‘workflow interruptions’ were considered the most prevalent stressors by most of the participants, as shown in Figure 2.

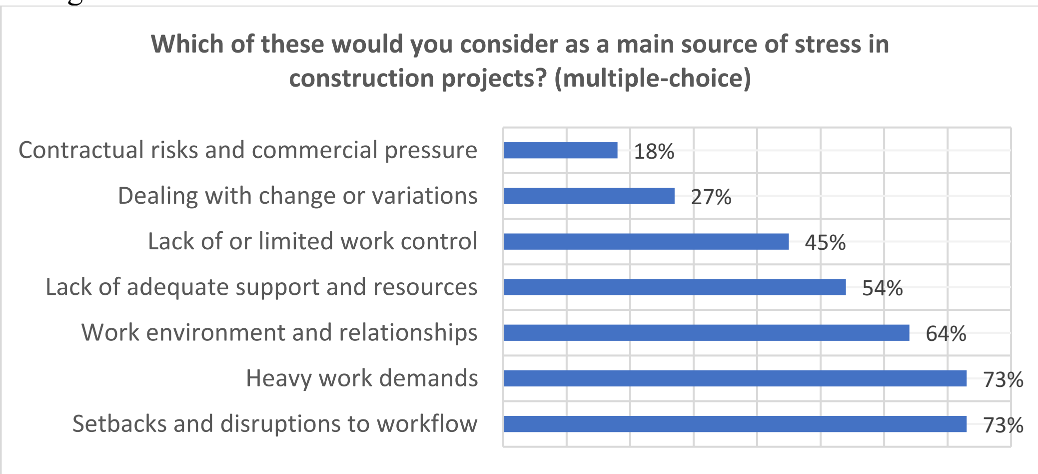

Figure 2: The Main Sources of Occupational Stress in Construction Projects

Following this, the participants were asked to assess the main causes of workflow interruptions as identified from the case-study. The participants were also provided with the opportunity to suggest any other factors and to provide any additional comments to support their answers.

MAIN CAUSES OF WORK-FLOW INTERRUPTIONS IN CONSTRUCTION PROJECTS

Two factors were agreed upon by more than half of the participants of the focus group as main causes of workflow interruptions in construction projects (see Figure 3). Some other suggestions and interesting comments were provided by the participants, as follows:

- *“It reflects the **culture** in construction not a particular site”.*
- *“Lack of building **the right team culture** to support the **collaboration** required”*
- *“Over promising on **unclear expectations**. Pressure then cascades to the team”*
- *“The **complexity** of the construction supply chain”*
- *“The **uncertainty** created by weather and conditions that we didn't know about”.*

As shown in Figure 3, the findings suggest that the work-related stresses that construction workers may experience in construction projects mainly stem from the pre-construction stage. In particular, it appears that both the construction programme and design could have a significant impact on the performance, mental health and wellbeing of the people working on site. Thus, the following questions (see Figures 4-6) were introduced to identify and gain a better understanding of the limitations and potential sources of stress embedded in the way we traditionally design, plan and procure construction projects.

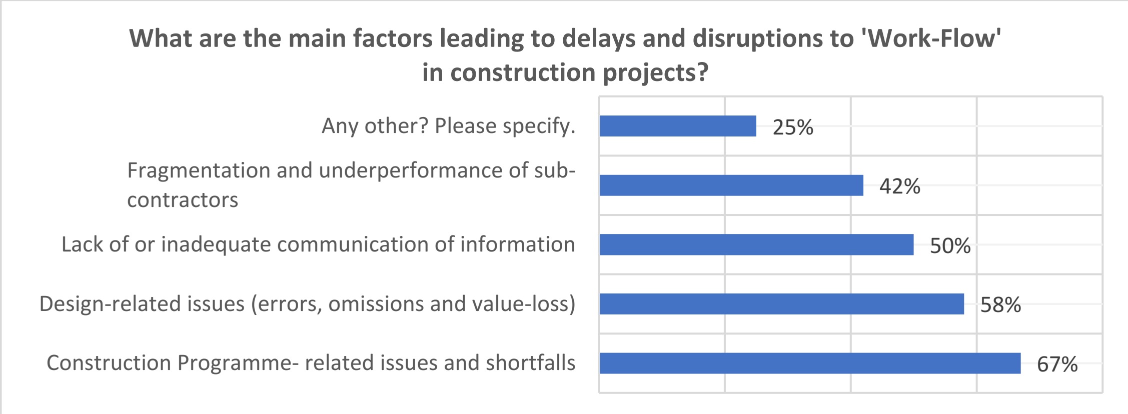

Figure 3: Main Factors Leading to Delays and Disruptions to Workflow in Construction Projects

Construction Programme-related Shortfalls

The participants criticised traditional planning techniques used in construction, based on the critical path method (CPM). The main concern raised is that CPM leads to the development of static programmes that do not account for the high level of uncertainty that characterise many construction projects (Figure 4). CPM is used to manage work in projects by pushing trade crews to deliver work based on schedules prepared weeks, or even months, before the project even starts (Koskela et al., 2014; Mossman and Sarhan, 2021); this leads to unnecessary stresses and frustrations for people working on site. As stressed by one of the participants "in competitive bidding situations, the programme is often tightened by corporate management staff in order to win the project - even though the bidding teams may not be the ones eventually delivering the project". In addition, CPM does not take into consideration the coordination between the trades that is required to allow work to flow.

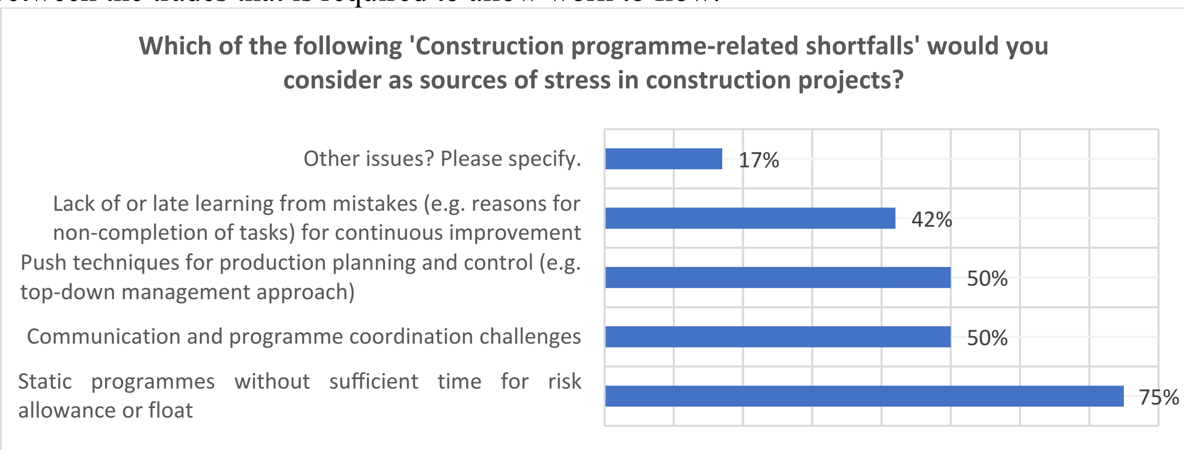

Figure 4: Construction-Programme Shortfalls as Sources Of Stress in Construction Projects

Design related Issues

Design changes were considered as a major source of stress and frustration in construction projects (Figure 5). Interestingly, design changes have been reported in many studies as a common problem in construction, due to its influence on project performance (see for example, Cox et al., 1999; Gharaibeh et al., 2021). However, there are hardly any studies that have considered their impact on the mental health and well-being of project participants.

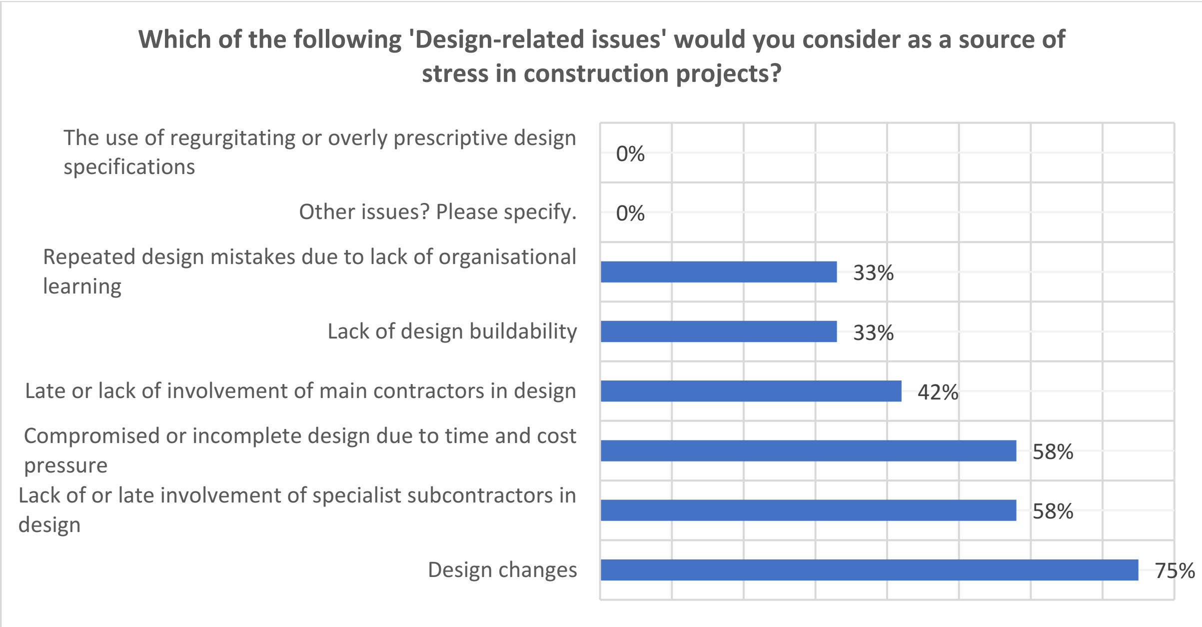

Figure 5: Inefficiencies in Design as a Source of Stress in Construction Projects

Design changes in construction usually occur due to: (1) changes in client requirements and value engineering purposes (2) design errors and omissions. From a lean perspective, there should not be a major concern with client changes during the project, as creating customer-value is part of the job. It is the responsibility of the delivery team to explain the change to the workers once they have ensured that the client understands the cost and time implications of the change and agrees them. However, as one participant reported, stress in construction projects usually occurs due to *"unrealistic changes made by the client organisations without fully understanding the impact that the change will have on the delivery team"*. Obviously, changes due to design errors or emissions lead to rework – that is waste. However, these design-related changes may not always be frustrating for everyone, as it could be argued that more work to do can be beneficial for the contractors and tradesmen involved, if they are compensated and feel valued.

Two other important design related issues were selected by the majority of the respondents as potential sources of stress. One is concerned with the need for engaging specialist subcontractors in design. This was also described by a participant as follows: "*main contractors have a very skeleton staff - the bulk of the work is done by specialists and these people can be missed out of the loop - especially M&E*".

The other issue relates to the contractual and commercial pressures that seem to influence the quality of design (for example, late or low payments). Interestingly, it was suggested in the focus group that "*designers need to be made more aware of occupational health issues within construction and not leave the contractors to sort it out*". Thus, it seems that design can play a major role in preventing or reducing stress in construction.

Both of these reasons point to the value of procuring construction with IPD or Alliance relational contracts that bring the whole delivery team together at the earliest stages of a project.

Contractual and Commercial Pressures

Most of the participants agreed that 'single-stage competitive tendering based on cheapest price and shortest programme' is a prevalent yet stressful practice (see Figure 6). Other factors were highlighted including 'contractual and commercial pressures; this has been described by a participant as follows:

> *"Commercial assumptions in the bidding phase can be over optimistic. I believe there has also been a trend for clients to push risk further downstream into consultants and contractors without necessarily allowing the budget to deal with those risks adequately in advance".*

There was also an emphasis from the participants on the importance of 'early involvement' of key members of the supply chain to support collaborative costing and design (Zimina et al., 2014; Namadi et al., 2017). For example, it was stated that "*the whole team of client, contractor, designer and the supply chain need to be engaged as early as possible - even at concept stage - so that there is full understanding of what is to be delivered and for how much!"*

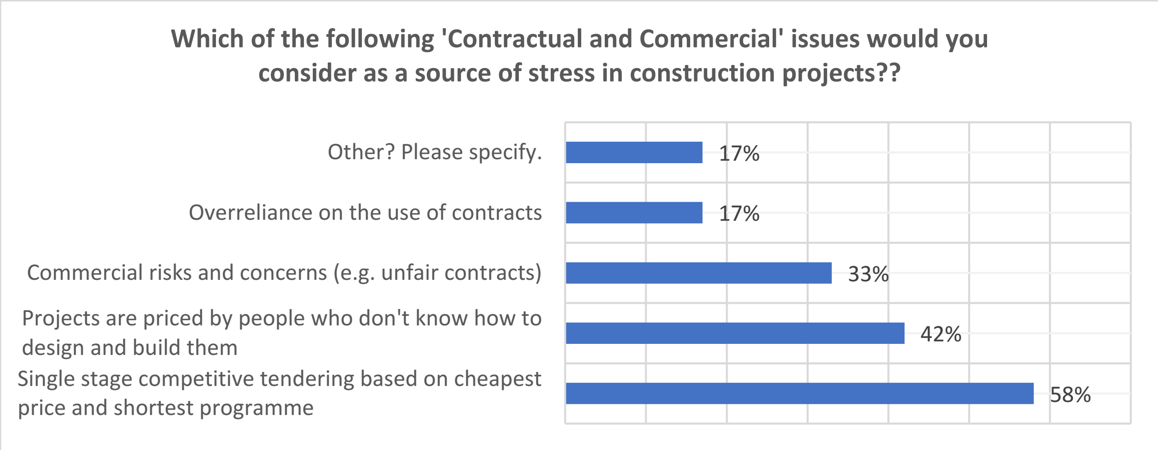

Figure 6: Contractual and Commercial Issues Influencing Stress in Construction Projects

This section has discussed the main sources of stress in construction projects revealed by this study, and it focused particularly on workflow interruptions and their causes. The next section looks at the findings in relation to stress prevention and reduction.

Strategies For Preventing or Minimising Stress in Construction

Common organisational practices for managing occupational stress used in construction tend to be 'reactive' rather than 'proactive'. Reactive practices include, for example, the use of fair and inclusive HR policies, offering counselling services, employee assistance programmes, and mental health awareness, training and first aiding — knee pads if you like. There are very few, if any studies, that have focussed on identifying or investigating strategies used at a project level. The following question, therefore, included a list of 'preventive measures' at a 'project supply-chain level' as identified in this study.

As can be seen in Figure 7, 'inclusive and collaborative planning' was the most recommended strategy for stress reduction in construction projects. This is an interesting finding, especially since the majority of the focus group have never heard of or used the Last Planner® System (LPS) for production planning and management – also known in the UK as 'collaborative planning'. This, therefore, suggests that the lean construction community can play a major role in promoting and improving mental health in construction through using and testing relevant LC theories and practices, such as the LPS, 5S, Target Value Design (TVD), and visual management techniques.

The effects of the implementation of the LPS on projects in Denmark (Thomassen 2003) appear to confirm the idea that predictable flow creates much less stress on projects. In the Danish projects that used LPS, sickness absence fell by 65%. It is generally accepted that sickness absence is associated with work stress.

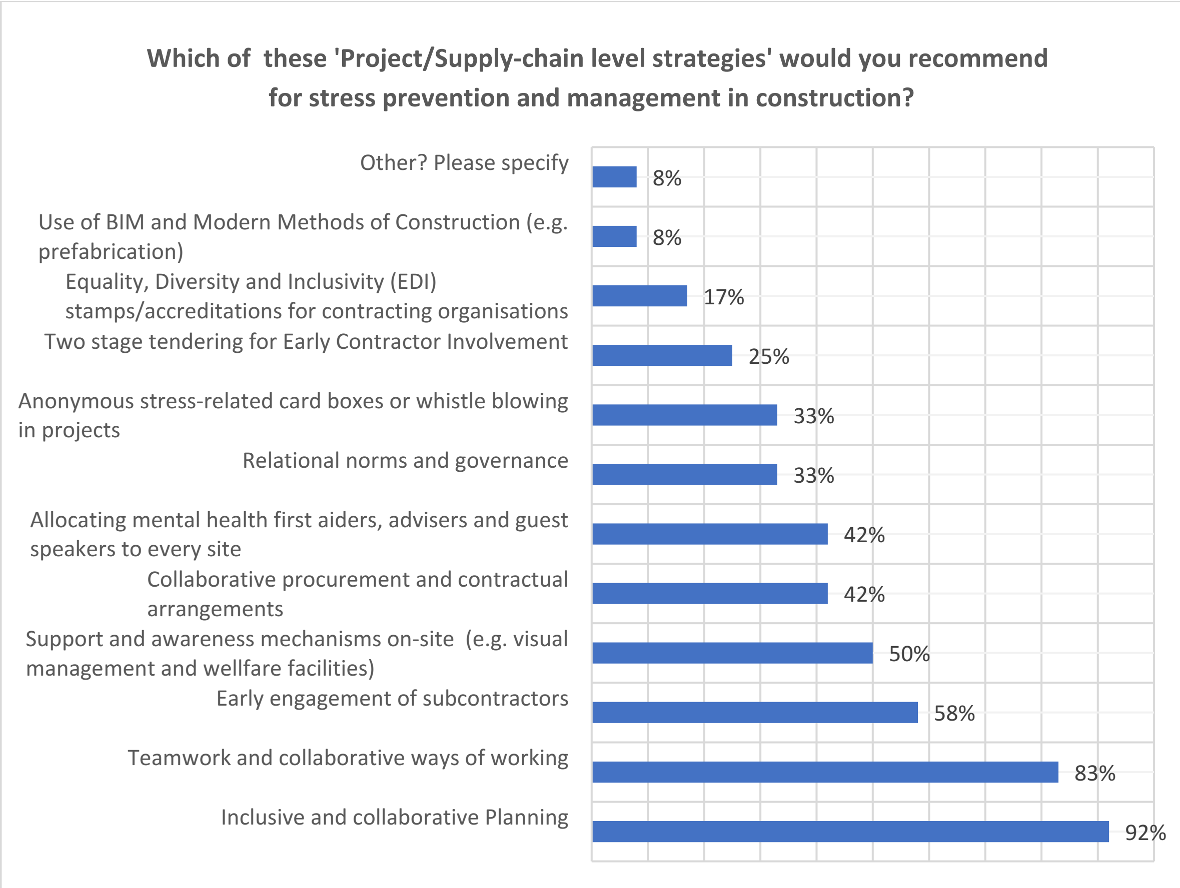

Figure 7: SCM Strategies for Reducing Occupational Stress in Construction Projects

TOWARDS A RESEARCH AGENDA

The empirical findings of this study have indicated that ‘workflow interruptions’ are a common and severe stressor in construction that can seriously affect the construction employee’s job performance and well-being. This raises the following fundamental question (RQ):

> **RQ:** ‘How can work-related stress and mental health considerations be incorporated into production planning and control processes in construction?’

This question is introduced to encourage further empirical research and foster an IGLC research agenda for addressing mental health issues in construction. One suggestion is to incorporate the HSE’s Management Standards (see HSE, 2019) into the Look Ahead Planning phase of the LPS when tasks in the Look Ahead period are *made ready* (i.e., constraint free) for the construction crew to deliver them when they want to (Mossman and Sarhan, 2021).

The UK’s HSE Management Standards are designed as a guideline for effective stress management. They address six key areas of *work design* that, if not properly managed, can lead to poor health and wellbeing, lower productivity and increased sickness absence (HSE, 2019). The Look Ahead window is when *work* is Made Ready. We also need a process for making *workers* ready. The six item HSE “checklist” is: (1) Demand – *e.g. can you cope with the demands of your job?*; (2) Control – *do you have a say in how your work is planned?*; (3) Support – *do you feel supported in your work?;* (4) Role – *are you clear about your role and responsibilities on the project?;* (5) Relationships – *can you have an open and honest conversation with people at any level in any organisation on the project?;* (6) Change – *is change well managed on the project?*. (For more detail on the checklist see HSE 2019)

The findings of this study, augmented by further empirical studies on the links between the concepts of *workflow* and *work-related stress* in construction, have potential to influence policy by incorporating ‘flow’ into the HSE’s Management standards for stress prevention and management.

It has been previously argued that the IGLC community should rethink the prevailing conceptualisation of ‘waste', so that it can account for both ‘environmental wastes’ (e.g. carbon emissions and energy consumptions) and ‘social wastes’ (e.g. unhealthy and unsafe practices) rather than focussing merely on process and physical wastes (Arroyo and Gonzalez, 2016; Sarhan et al., 2018). This study echoes and contributes to these arguments, by suggesting that the sources of stress (i.e. stressors) in construction projects be classified as ‘social wastes’. The stressors identified here could also be classified as sources of process waste in construction.

CONCLUSION

This study was conducted to explore the concept of ‘occupational stress’ in construction and has led to novel contributions to knowledge. ***First***, the study identified seven main sources of stress in UK construction projects (Figure 2). ***Second***, the findings of this study revealed that ‘workflow interruptions’ are the most significant source of stress in the construction project studied. It is, therefore, suggested that strategies for stress-reduction in construction should focus on finding innovative ways for enhancing workflow in construction. ***Third,*** it is suggested that policymakers should consider the potential for incorporating ‘flow’ into the HSE’s Management Standards. This study also identified two main causes of workflow interruptions in UK construction projects: (1) Construction Programme-related shortfalls; and (2) Design-related issues. Accordingly, the importance of engaging specialist sub-contractors in both design and construction programme development has been highlighted. ***Fourth***, it is suggested in this study that ‘stress’ and ‘risks’ are closely related in construction, as both tend to be pushed and transferred down the supply-chain. In particular, ‘single stage competitive tendering based on cheapest price and shortest programme’ has been identified in this study as a deeply rooted source of stress and value-loss in construction projects. ***Fifth***, ‘inclusive and collaborative planning’ is identified by the participants of this study as the most recommended strategy for stress prevention and/or reduction in construction projects. Accordingly, this study suggested incorporating the HSE’s Management Standards into the Look Ahead Planning phase of the LPS. ***Finally***, the study formulated new research questions and ideas, to contribute towards fostering an IGLC research agenda for tackling mental health issues in construction.

OPPORTUNITIES FOR FURTHER RESEARCH

This study focused on a single project. There are opportunities to do similar research on other projects in the UK and elsewhere in the world. There are also opportunities to use radically different research methods to see if they come up with similar or different results. It is suggested that further studies could also focus on investigating the sources and impacts of occupational stress on the productivity of different levels of workers within the construction project context.

Future studies are encouraged to investigate how lean design (e.g. TVD) and contractual arrangements (e.g. relational contracts) influence the mental health conditions of the project teams and workers involved. Furthermore, there is also scope for investigating the roles that emerging technologies and visual management techniques could play in supporting both ‘workflow’ and ‘stress reduction’ in construction projects.

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INVENTORY AND PILING WASTE: A COMPUTER VISION APPROACH

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ABSTRACT

Construction sites contain a lot of waste, and eliminating it enables productivity gains and health and safety improvements. Computer vision is a promising technology that is being used in various construction applications. Construction sites with limited human resources could benefit from automated computer vision-based waste analysis. This paper presents preliminary findings related to the algorithm-based waste detection of piling works and explores potential applications from a visual management perspective. An experimental approach was used in the study, and images from a construction site in Finland were used to train the algorithm. The main findings revealed that the amount of waste shown by the images was substantial and that ground-level and drone images could be combined to create a comprehensive view of pile waste inventories. This paper also presents potential applications of image-based pattern recognition for infrastructure sites where the use of drone and ground-level images is standard practice. Several problems emerged when using transfer learning to train the algorithm, the most significant of which were variations in the scenery of images used for training and the limited number of images. The solutions to these problems lie in collecting more data and experimenting with other deep learning-based methods which will be explored in future.

KEYWORDS

Lean construction, waste, visual management, computer vision, piling.

INTRODUCTION

WASTE IN CONSTRUCTION

Since the beginning of the 1990s, the construction industry has been inspired by the manufacturing industry's lean management school of thought and used its tenets as guidance when solving long-term construction problems related to unreliable planning, uncertain production flow and productivity, constant delays, and budget overruns (Koskela, 1992; Koskela et al., 2002). One of the principles of lean management is identifying and eliminating production-related waste, which interrupts production flow and increases operating costs (Ohno, 1988; Shingo, 1985).

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Ohno (1988) identified seven types of waste: overproduction, transportation, stock on hand, idle time, processing, movement, and the production of defective products. The identification of waste in construction industry activities has become a fruitful research field, relating the waste in construction sites, the complexity of construction activities, and production flow interruptions (Koskela, 2004; Koskela et al., 2013; Macomber & Howell, 2004).

Since identifying waste in dynamic environments, such as construction sites, is time consuming and challenging (Lee et al., 1999; Achell et al., 2013), the construction industry once again looked to the manufacturing industry for a supportive tool and identified Gemba walks as an ideal option. The Gemba walks concept was implemented by Ohno (1988) in the car manufacturing industry and described by Womack (2011) as a management practice used to grasp the current situation before acting. Gemba walks can be connected to the visual management (VM) concept of being able to collect the information available at a site with a glance (Galsworth, 1997). The people involved in Gemba walks must know how to correctly identify waste during construction site walkthroughs. Time, training, and team commitment are required to develop this skill (Kerem et al., 2013).

VM was mainly developed to meet the practical needs of the manufacturing industry related to information-based problem solving through the use of simple visual aids and tools (Tezel et al., 2016). In addition to the simple tools of VM, new technologies, such as CV, have been proposed for use in safety management, progress monitoring, productivity monitoring, and quality control (Paneru & Jeelani, 2021; Tezel & Aziz, 2017). CV can support the identification of waste connected to overproduction and inventories. State-of-the-art CV algorithms can detect objects with the help of feature extraction. The use of CV algorithms to identify and reduce construction waste is a promising area of research (Wang et al., 2020). By using CV algorithms to identify objects, construction waste can be significantly decreased.

COMPUTER VISION

CV is the science of recognizing objects of interest with minimal human intervention. CV supports the automation of tasks that require visual assessment. This makes CV an important technology for the automatic detection of critical tasks in construction. One of the growing needs of utilizing CV is rapidly, accurately, and comprehensively understanding a dynamic construction site (Martinez et al., 2019). This visual assessment can have many applications, including construction progress monitoring, construction site safety management, construction waste management, and quality control of building elements.

According to an elaborate review by Martinez et al. (2019), CV has mostly been used to enhance construction site safety by tracking equipment, materials, personnel, and other resources. Next prominent utilization of CV is in productivity analysis by activity monitoring and scan-to-BIM (Building Information Modelling) to obtain an as-built situation from a construction site (Golparvar-Fard et al., 2012; Masood et al., 2020). In addition, CV methods have been developed for inspection and condition monitoring of infrastructure (Bay et al., 20008). No significant research on the combination of CV and construction waste management was conducted before 2019 (Martinez et al., 2019). However, a few research papers after 2019 have focused on construction waste management using CV as discussed in the next paragraph.

Much of the waste-related literature explores the detection of concrete, bricks, plastics, foam, stone, timber, and other types of construction waste (Davis et al., 2021; Na et al., 2022; Seunguk et al., 2022; Song et al., 2022; Zhou et al., 2022). The main objective of previous research was recognizing waste in building construction works through the use of CV and deep learning models. Wang et al. (2019) developed a construction waste recycling robot with the help of CV. The robot used R-CNN (Recurrent Convolutional Neural Network)-based object detection to find scattered nails and screws in real time so that those objects could be collected and recycled. Also, Wang et al. (2020) used SLAM (Simultaneous Localization & Mapping) and instance segmentation to recognize residual pipes and cables. The methodology involved guiding a robot in on-site waste sorting and recycling. Most of the aforementioned works focused on small projects, such as building site construction waste, which includes common building materials. Research on the use of CV in large infrastructure sites and piles is limited.

The present study focused on inventory-related waste accumulated during piling work at an industrial construction site. Furthermore, it explored how CV can be applied for more efficient waste identification and better visualization of the waste problem of providing visual identification of the waste as a VM tool.

DATA COLLECTION AND SETUP

The data was collected from a 70-hectare industrial construction site in Finland. Pile waste inventories (PWI) were observed within a 22,000-square meter area, which included one building. During the observation period, the construction site was mainly in the piling work phase, although work phases in which foundations, concrete frames, and underground pipelines and power cables were built parallel with the piling works.

The data was collected over a 27-week period from March 2021 to September 2021, and the images included spring, summer, autumn, and snowy periods. Each week, ground-level photographs were taken by the site supervisor, and drone images were taken by the measuring team. The approximate distance between the ground-level photographer and the piles varied from a few meters to hundreds of meters. Regarding drone photography, the vertical distance between the camera and the ground varied from 55 meters to about 145 meters. Of the 563 drone images obtained, 21 were included in this study. In addition, 212 ground-level images and 29 combined orthographic images (i.e., a combination of several drone images of the entire site area) were included in the analysis.

The first step in any CV- and artificial intelligence (AI)-related problem is the creation of an annotated dataset that has all classes. For this purpose, the researchers saved the images to a cloud service and then annotated them using a freeware labeling software program called makesense.io. Four categories were used as classes: 0) concrete pile cut-off inventory, 1) steel pile cut-off inventory, 2) concrete pile inventory, and 3) steel pile inventory. The first two consisted of cutting waste or broken piles left after the piling work was completed, while the other two comprised intact piles that had not yet been driven and were in temporary locations on the construction site or next to the pile-driving rigs. Although there was a considerable number of images covering the site area, at the end of the labelling task, only 110 images were used. These were the images that contained one or more of the four categories of classes.

The CV setup was based on transfer learning, which involves initially training a neural network on a small dataset instead of one with thousands of images (Pan et al., 2009). The weights from the pre-trained neural network were improved by using features from ground-level and drone images containing PWIs. YOLO v7 which is a deep learning algorithm was chosen for object detection because of its accuracy and speed (Wang et al., 2022). The YOLO algorithm is originally trained on a set of common objects including a car, a hat, an umbrella, dogs, a door. To detect objects from the construction site, the algorithm parameters were changed based on the features of images with piles. 110 images with a total of 535 labels, including all four classes, were used to change the parameters of the trained YOLO v7 model with the resolution of the images as 4608 × 3456. Processing such a large image for a neural network requires a very high memory and processing power. To avoid CPU and GPU limitations, the algorithm was set up using Google Collaboratory services.

ANALYSIS

During the manual labeling process, 535 PWIs were identified in the images. Specifically, 233 were identified from images taken at ground level, and 302 were identified from drone images. In the ground-level images, 64.4% of the PWIs were concrete PWIs, and 35.6% were steel PWIs. Of the designed and driven piles, 84.6% were concrete piles, and 15.4% were steel piles; the number of steel PWIs was proportionally higher than expected based on the number of designed piles. In the drone images, 63.6% of the PWIs were concrete piles, and 36.4% were steel piles. Furthermore, 54.5% and 37.4% of the PWIs detected in the ground-level and drone images, respectively, were cut-off PWIs. Moreover, temporary pile inventories for piling work purposes (located near piling rigs) comprised 45.5% of the observations in the ground-level images and 62.6% in the drone images. Table 1 shows the observed PWIs.

Table 1: Observed pile waste inventories.

Waste class	Observations from ground-level images	Observations from drone images
0. Concrete pile cut-off inventory	95 (40.8%)	102 (33.8%)
1. Steel pile cut-off inventory	32 (13.7%)	11 (3.6%)
2. Concrete pile inventory	55 (23.6%)	90 (29.8%)
3. Steel pile inventory	51 (21.9%)	99 (32.8%)
Total	233 (100%)	302 (100%)

Figure 1 illustrates examples of classified PWI observations. The top two images are typical pile cut-off inventories after pile driving, while the other examples are typical work-in-progress inventories near pile rigs. Outside of the research location, there was a larger buffer storage area for piles; that area, the size of the buffer inventory, and buffer fluctuations were not explored at this stage of the study.

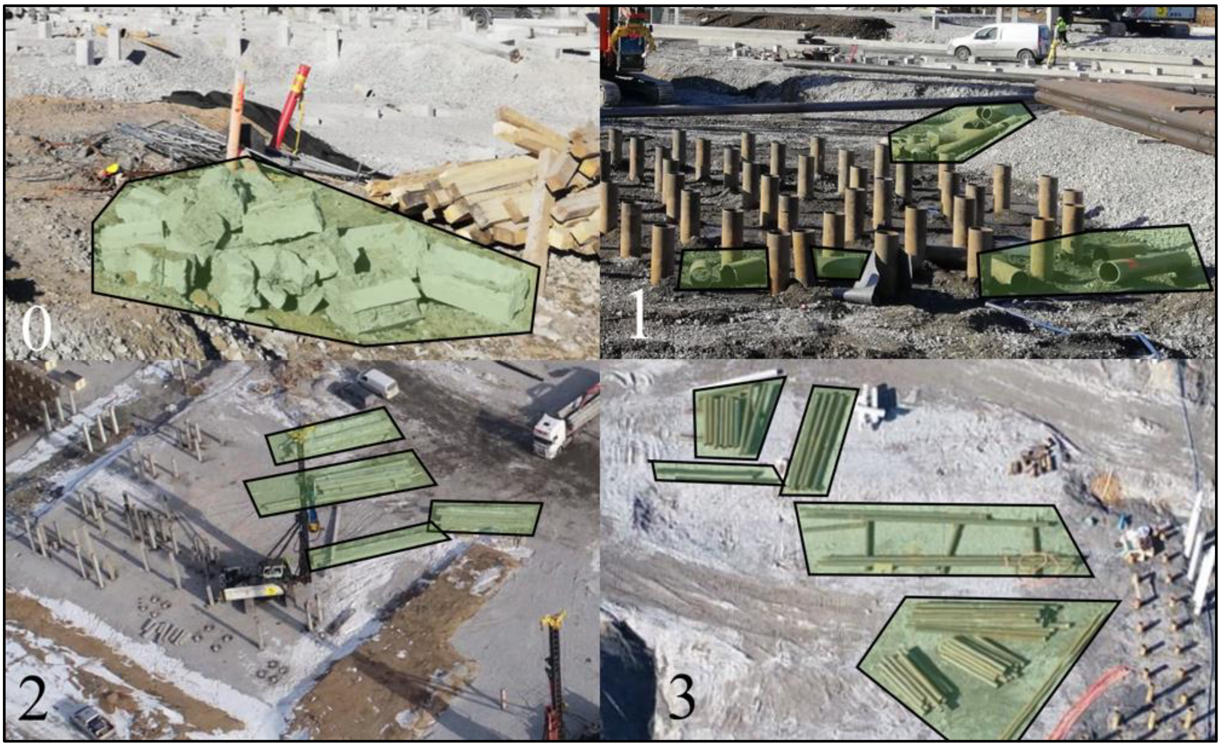

Figure 1: Four Examples of Observed Pile Waste Inventories

The green boundaries shown in Figure 1 correspond to the labeling used to teach the algorithm to identify PWIs. The numbering corresponds to the waste classes in Table 1. Figure 2 shows the observations obtained from the ground-level images of waste inventories over time.

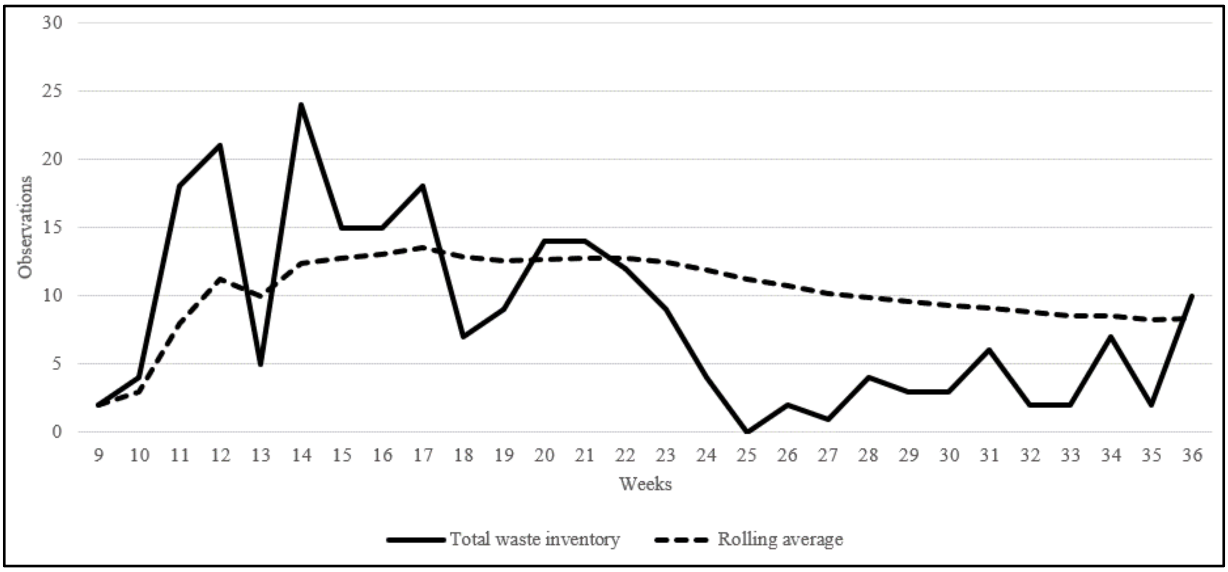

Figure 2: Observed Waste Inventories Over Time: Ground-Level Images

The number of PWI observations in the ground-level images increased after the piling work started and reached an average of 13.9 observations per week between Weeks 11 and 23. Once the summer holiday period started, the number of PWI observations dropped to average of 3 observations per week between Weeks 24 and 35, increasing only at the end of the observation period in Week 36. The average number of observations over the entire period was 8.3 per week. Figure 3 shows the corresponding PWI observations from the drone images.

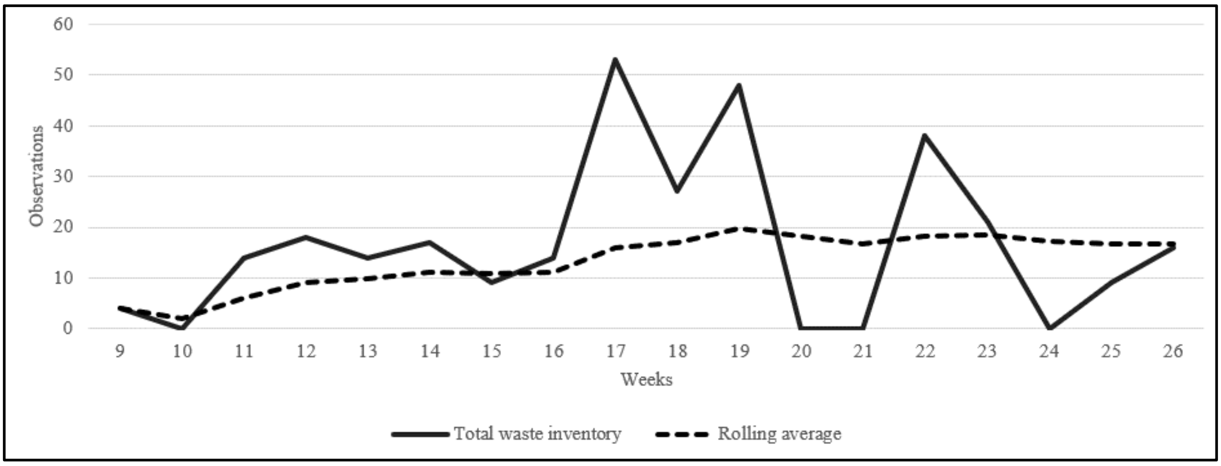

Figure 3: Observed Waste Inventories Over Time: Drone Images

The PWI observations from the drone images differed from those from ground-level images. Between Weeks 11 and 23, the average number of observations was 21 per week. In other words, about twice as much pile waste was observed in the drone images as in the ground-level images. During the summer holiday period, only 2 weeks were observed; there were 9 observations in Week 25 and 16 in Week 26. In Weeks 17–19, there was a clear peak in PWI observations, with an average of 42.6 observations per week during that period. The average number of observations over the entire period was 16.8 per week. Therefore, about twice as many PWI observations were made from the drone images as from the ground-level images.

Figure 4 shows the number of piles driven in pieces and the number of PWI observations. The amount of PWI observations was largely in line with the progress of the piling work.

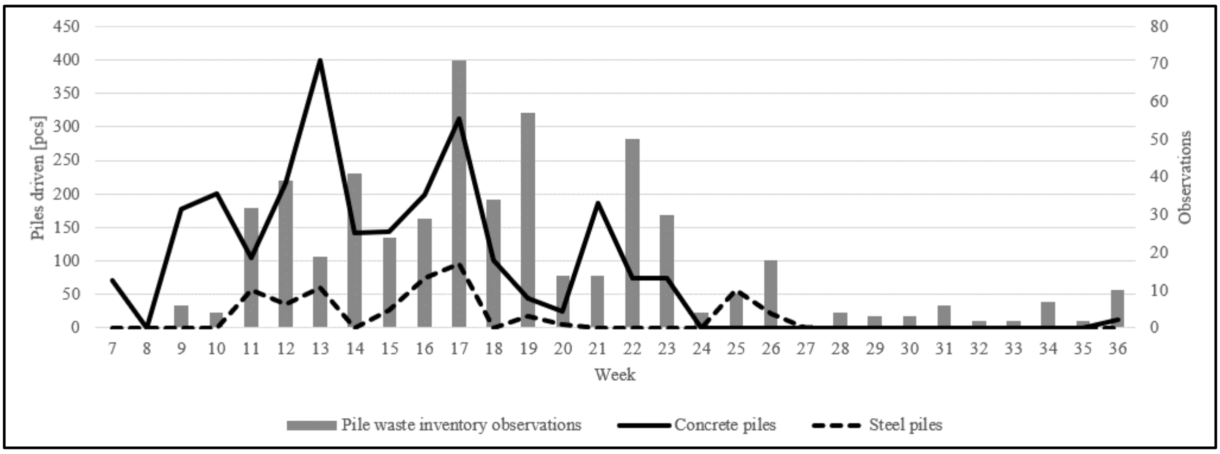

Figure 4: Piling Progress and Pile Waste Inventory Observations

To summarize the waste observation results, the amount of cut-off waste was significant—37,5% to 54,5%, depending on the observation method (a photo taken by a human from the ground level vs. a photo taken by a drone). Twice as many waste piles were detected in the aerial images taken by drones as in the ground-level images taken by supervisors. Regarding the observation area (22,000 m2), the average number of PWI observations was 0.001 per square meter, with a maximum of 0.003 observations per square meter (drone images). Since cut-off waste is smaller in size as compared to full pile, the high altitude of the drone photography may have contributed to the less frequent cut-off waste observations compared to the ground-level photography. Meanwhile, since twice as many PWI observations were made from the drone images, it can be assumed that the high-resolution drone images also included all of the PWI observations made from the ground level. These likely duplicates were not investigated in or removed from the present study because the primary purpose of the images and the waste observations was to train the algorithm; obtaining a large number of images and observations, despite possible duplications, supported the learning of the algorithm.

OBSERVED CHALLENGES IN THE SETUP AND COMPUTER VISION

In the first experiment, full-resolution images were taken to train the neural network. The first experiment was conducted for 50 epochs. This means that the algorithm read the images at least 50 times to derive features from them When the images were read in a batch size of eight, Google Colab crashed; however, the image reading process worked for a batch size of four. A recall and mean average precision (mAP) of less than 10% was achieved in the first trial. For the algorithm to detect any relevant information from a new image, a recall and mAP of at least 50% is desired.

For the second experiment, the image size was reduced to 920 × 720, the batch size was 8, and the number of epochs was increased to 100. Although recall in the 93rd epoch increased to 43.5%, the model was unable to detect the PWI while testing on a new image. This result can be attributed to various considerations. One possible reason could be that most images had multiple labels, a large image size, and objects that seemed smaller as compared to other objects in the high resolution imagery; therefore, the algorithm was unable to properly learn the features of these images. Another reason could be that the dataset was too small; for object detection, neural networks are generally trained on about 1,000 images. When we reduced the size of the images, some information was lost from the pixels. Another important challenge was that the site was very dynamic, and the images had variable backgrounds because they were taken during various seasons. For CV, it is desirable to use a training image with some kind of similarity within the features and background of the images, so that the algorithm can better detect the features of objects of interest.

DISCUSSION AND CONCLUSIONS

Waste identification and elimination are the main principles of lean construction (Koskela, 1992). As such, it is essential to visualize waste and identify it properly. VM can provide real-time visualization and support improvements during the construction phase. Given the increasing prevalence of digitalization and efforts to employ it at construction sites (Martinez et al., 2019), technologies can also be incorporated into DVM (Digital Visual Management) devices, providing updated information and real-time understating of the construction site reality leading to decentralized decision-making (Koskela et al., 2018; Reinbold et al., 2020). The present study builds on the contributions of Tezel and Aziz (2017), Li and Liu (2019), and others who have combined VM and drone technology in an infrastructure construction context.

The study data (i.e., the area images) was collected manually by site supervisor during site visits, and differences in the images inhibited the use of CV for data analysis. Manual data collection poses obstacles because it is time consuming and costly; nonetheless, it remains the main form of data collection in construction sites (Kerem et al., 2013). The shift to digitalized means of data collection in construction sites will enable not only the collection of data in a shorter timeframe and with lower costs but also the provision of data that is better suited to the use of CV and other AI technologies in the future.

Since cut-off waste is smaller in size, the high altitude of the drone photography may have contributed to the less frequent cut-off waste observations compared to the ground-level photography. The large number of PWIs observed in the drone images compared to the ground-level images may indicate that supervisors choose a tidier viewpoint because such images are typically used in reports sent to clients. In this respect, drone photography may be a less unbiased way of collecting PWI information from an infrastructure site (Flyvbjerg, 2021). Meanwhile, since twice as many PWI observations were made from the drone images, it can be assumed that the high-resolution drone images also included all the waste observations made from the ground level. These likely duplicates were not investigated in or removed from the present study because the primary purpose of the images and waste observations was to train the algorithm; obtaining a large number of images and observations, despite possible duplications, supported the learning of the algorithm.

The trained model was unable to detect piles in images; however, there was positive foresight as recall went from 10% to 43.5% in the second trial. Reliable pile detection results could be achieved in the future by increasing the training data and employing mid-range image resolution. In addition, dynamic site conditions and background variability may be achieved by obtaining more images per season from different perspectives. Our future work will include training the algorithm with a larger annotated dataset and exploring different algorithms that can handle remarkably high-resolution drone images.

The present study contributes to the development of approaches for determining how CV could be used for achieving lean construction. CV has become a tool for understanding the actual situation in many applications, such as self-driving cars, and construction progress monitoring. The technology can be utilized to improve lean construction practices. For example, CV can be used to streamline the process of observing any construction material inventory or waste which is a subjective process in the construction industry in the current scenario. CV can also be used to generate new types of data for the visual management of construction sites. Furthermore, by comparing both types of datasets (i.e., ground- and drone-based images), we were able to identify challenges in each. For drone images, the coverage is wide; however, the objects appear smaller. For ground-level images, objects are more identifiable in images with a tidy appearance. This work can also be used to determine the most useful dataset for monitoring construction inventories and waste on large infrastructure sites.

One of the lean principles is based on 'maximising value while minimising waste' (Ohno, 1988, p.175). Minimizing waste is essential to enable professionals to deliver increasingly higher value. It is usually difficult to estimate the amount of waste without conducting an inventory. The present study can be used as an example of how waste and excess or misplaced inventory can be identified using CV. This study also demonstrates that it is possible to develop a CV-based tool for inventory management on construction sites alongside existing manual inventory and waste identification methods.

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SUSTAINABILITY AS TARGET VALUE – A PARAMETRIC APPROACH

Sebastiano Lombardo[1], Arve Hindenes[2], Sigmund Aslesen[3], and Sigmund Reff[4]

ABSTRACT

Our time is characterized by climate changes that impose sustainability in every industrial activity, an additional objective to our design and construction processes. The classic Lean Construction approach needs to be further developed to take sufficient care of the sustainability issue. The design of modern buildings is a work process that can be set up and run with tools that secure a more sustainable final product. This study proposes to extend the classic range of objectives pursued by the Lean construction approach, as to include sustainability in the design process, in a systematic and structured way. The case of a building project is analyzed. In the early design stages, advanced structural design tools are used to explore various alternative designs of the bearing structure. The structural design tools are combined with tools used to calculate embodied carbon in the construction. The levels of embodied carbon following each of the many possible, alternative, structural solutions are estimated. These insights are provided to the owner in a very early stage of the design process. Through these design practices owners and investors can add sustainability targets to the classical project targets (cost, quality, time), and include sustainability as a part of the fulfillment of the client's functional needs.

KEYWORDS

Lean construction, Target Value Delivery (TVD), sustainability.

INTRODUCTION

Lean production thinking applied to construction management has evolved since 1940. Today it represents an approach to facilitate and secure value creation for the client as well as the actors involved in a construction project (Abdelhamid et al. 2008). Although the concept of value may be defined in various ways (Lombardo et al. 2017), in construction projects value is often understood as the fulfillment of the client's functional needs, and of the financial objectives of all involved actors (Drevland and Klakegg 2017). This understanding of value entails the set-up of project objectives like low production costs, optimized production flow, waste reduction, alignment of design and production, and pull production planning (Kalsaas, 2020). These objectives remain within the technical realms of engineering and construction and are widely acknowledged as fundamental to achieving high levels of efficiency and quality in the AEC industry. The relatively recent introduction of practices like integrated concurrent engineering, virtual design and construction (Fischer et al. 2017), and last planner system (Ballard et al. 2000), capitalizes on this understating of value and this kind of objectives.

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In our times, climate changes impose the objective of sustainability on all of us, in every industrial activity, as a new objective to our design and construction processes. Although sustainability is an easy objective to embrace, work practices and tools are yet to be fully developed to secure a sustainable production process and a sustainable final product. This paper questions how sustainability can be an explicit goal of a construction project. And how can the design process support sustainability goals? This research witnesses the search for methods, tools, and practices aimed at introducing elements of sustainability in the construction design process.

LITERATURE REVIEW AND THEORETICAL APPROACH

LEAN APPROACH AND ITS LIMITATIONS

Waste reduction, workflow optimization, design and construction alignment, pull production planning are some of the concepts bound to secure a Lean construction process. A well-implemented Lean construction approach will help designers, and contractors, to focus on cost, quality, and performance objectives. The arguments in favor of including sustainability goals in the definition of project performance are well established in the literature both in terms of principles to be used to guide the design and construction (Bourdeau et al. 1998; Huovila & Koskela, 1998), and on work processes to be adopted at various design stages (Yates and Castro-Lacouture, 2018). Yet good intentions are often curbed by the boundary conditions provided by the project schedule and budget. Consider a large building that shall be designed and built. The number of possible alternative (architectural, structural, energy) solutions that can be studied is in fact quite limited. The designers may not have enough time and resources to analyze enough alternatives to find optimal solutions. Other restrictions may come directly from the very set of project goals adopted by the owner of the project. If sustainability, in any of its facets, is not included among the project goals, it is improbable that the final product be checked in that respect.

Therefore, the normal design approach based on optimizing cost, quality, and time does not necessarily end up in an optimal solution when it comes to sustainability. Two main questions arise:

How can sustainability be an explicit and ineludible goal of a construction project? And how can the design process of modern buildings be set up to support sustainability goals, such as “the reduction of greenhouse gas emissions”?

These are the research questions of this study, through which we propose an approach to extend the classic range of objectives pursued by the Lean construction approach, as to include sustainability, in a systematic and structured way. A clear definition of sustainability is needed.

SUSTAINABILITY DEFINED

The concept of sustainability is a complex one, and its definition may vary depending on the context in which it is used and may include social, ecological, cultural, and environmental facets. The 17 sustainable development goals of the United Nations (UN) provide a good framework to find a definition suitable to the purposes of this study. Under goal 13 – Climate Change - in particular, several nations explicit their commitment to reducing their greenhouse gas emissions (the EU committed to a 30% reduction, Norway to 55%) (NRK, 2022). The AEC industry may produce an impressive effort to contribute to this reduction. This view can be adapted to focus on the reduction of greenhouse emissions as the AEC industry’s main contribution to the cause of a more sustainable global development.

A THEORETICAL APPROACH TO SUSTAINABLE DESIGN

For a broader review of decision-making methods and how these may affect sustainability goal-setting in construction projects see Penadés-Plà et al. (2016). The approach this study proposes is based on putting sustainability as an explicit objective for the design to be developed, and on giving it the same importance as classic goals like "cost", "time" and quality". This approach largely resonates with the concept of Target Value Design (TVD) which is used to set up project objectives. TVD requires that a fixed goal is set for any given value to be achieved through the design process. Normally a target *cost* is considered relevant and important, along with a target *quality level* and a target for the final *delivery deadline*. The design work is then organized and managed to achieve those targets, following a specific set of rules to check misalignments thought the work process (Zimina et al., 2012). We build this study on previous research connecting sustainability and lean construction (Johnsen and Drevland, 2016) and propose here to set up a sustainability target in addition.

Provided that sustainability is a broad concept, and given the definition this study has chosen, the target to be used to guarantee that sustainability is considered among the project goals can be related to an effort to minimize the greenhouse gas emissions from the building construction project. This target must be quantified, approved by the owners, and implemented in each project phase, from early planning, through the design process and to construction and operations.

The method used to set up this target, and the work process applied in the project is presented in the following sections, limitedly to the early planning and design phases.

METHODOLOGY

This research is executed as an explorative in-depth study of one case. A general contractor company that normally adopts lean construction approaches and has clear ambitions within sustainability; the opportunity to witness a phase where project goals are about to be set; good access to informants and to the corporate database; made this case well suited to our research purposes. Data were collected over six months through non-participant field observations with the design team during the design work; semi-structured in-depth interviews of four key contributors; recording of project plans and project deliverables. To focus our study, our data collection was limited to the design phase of the HQ construction project and focuses on sustainability in the design process rather than on the product.

THE CASE STUDY

Veidekke is a large general contractor in Norway. The company is planning to build its Head Quarters in the Capital city and wants to use this project as an opportunity to contribute to the national effort to cut greenhouse gas emissions. The office building is about 20000 m^2, over five floors, including the cellar. Although the general geometry is defined by the architect, the solutions for the bearing structure, including foundations, are not defined from the start. This study focuses on the assessment of various solutions for the bearing structure, and how this part of the project has been designed to contribute to achieving the sustainability target.

The following alternatives can be considered for the bearing structure:

1. Traditional bearing system in hollow cores slabs (HC) and steel.
2. Traditional bearing system in bubble-deck slabs and steel.
3. Modular building with solid wood decks. Support in the form of glulam beams and columns (hybrid solution)
4. Cast-in-situ concrete solution with post-tensioned slabs.

For each alternative, a large number of variations can in theory be considered, depending on the geometry variables of the construction elements (e.g., walls, beams, slabs), the positions of the elevator shafts, and the solution chosen for the façade, just to mention the most obvious ones. There is therefore a large number of possible solutions to be assessed and, besides the tools that make such an assessment possible, it is necessary to know which criteria the final decision shall be based on.

FINDINGS

TARGET VALUES DESIGN AND CHOOSING BY ADVANTAGES

Target Value Design (TVD) is the approach Veidekke chooses to establish the criteria to be used in the choice of the preferred solution for the bearing structure. In this case, a target *cost* is set, together with a target for the schedule and project completion date before the design starts. A set of target values are set up to assure the qualities of the final product (e.g. room program, functions, materials, etc.). High *flexibility* in the use of the surfaces (floors, walls) during the lifespan of the building is another important target, along with maximal usage of Veidekke's *own resources* (workforce, production technologies). Finally, and most interestingly, a target value is also set up for the maximum allowable volume of greenhouse gas emissions. The building shall be realized with *50% lower emissions* than a comparable building being built in the same period, in the same region, with the most common solutions for design and construction methods. In addition, the new HQ building shall qualify both as Breeam Excellent and as Green Building according to the EU taxonomy (Rademaekers, 2014). Putting these targets influences all the design decisions and forces the designers to adjust their thinking and their choices to achieve these targets.

In the following section the set-up of the design process is described, to explain the approach, the work process, and the tools there were adopted.

THE DESIGN WORK PROCESS

Having received from the owner and the contractor the set of target values, which included a reduction by 50% of the emission of CO2 compared to similar projects in the region, the design team went on preparing the structural analysis that should deliver solutions within the given targets. The design process can be summarized in the following main steps:

Step 1. Architect provides the main geometry of the building (Revit model, LOD200).

Step 2. The main geometry of the building was given by the architects, the second step was to decide on the technology to be used to realize the bearing structure. The first two structural solutions to be analyzed, were the two main variants with steel frames and prefabricated slabs: (alt. 1 post-tension slab and alt.2 use of bubble deck).

Step 3. Given the main geometry and one alternative of the bearing structure, the designers and the contractor identified the geometrical elements, or variables, of the bearing structure that should/could be modified (position and dimensions) in order to explore many variants of the given solution.

The following variables were considered:

- Location and dimensions of piles
- Position and dimensions on columns
- Location and dimensions on load-bearing walls
- Location and typology of slabs
- Floor heights
- Location of bathroom cabinets
- Location and size of lift, stair and technical shafts
- Placement of tension cables, if any, in the plane and in the cross section

Step 4. The list of variables to be considered flexible was used to set up a parametric model (in Grasshopper software) of the bearing structure. This model allows the simultaneous variation of a given number of the above-mentioned variables, and the creation of as many sub-alternatives of the given structure.

Step 5. Besides the geometrical model (e.g., Revit, LOD200) components (materials, loads) to be used for the structural calculations are *also* included in the parametric model. A full-fledged Finite Element Model (FEM) in SAP 2000 (a structural calculation tool) is contained in Grasshopper and interconnected with the Revit model. In this way, any change in the geometry entails new figures in the finite element analysis. For any given geometry a complete FEM analysis is delivered, and a preliminary structural analysis verification is automatically performed.

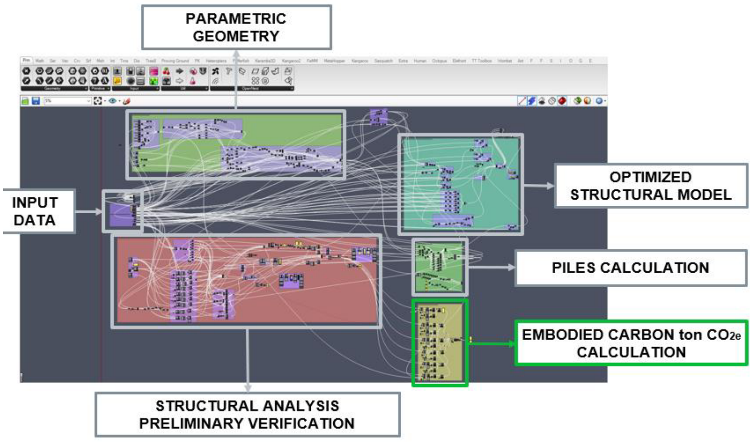

Figure 1: Parametric Model (Grasshopper) including Geometry, FEM and CO2 calculations

Step 6. Software, for the estimation of the emission of CO2 equivalents (in this case OneClick LCA) is plugged into the parametric model. Given a geometric and a structural solution (including the chosen materials) for any given alternative bearing structure an estimate of the greenhouse gas emission is delivered, provided that the Environmental Product Declaration of the elements used in the structure is available.
Step 7. An optimization plug-in for Grasshopper (in this case Opossum), including two of the best-performing, single-objective optimization algorithms is launched and, after some necessary iterations, a solution is optimized to minimize the volume of CO2 emissions.

The process from Step 2 to Step 7 is iterative, as shown in Figure 2.

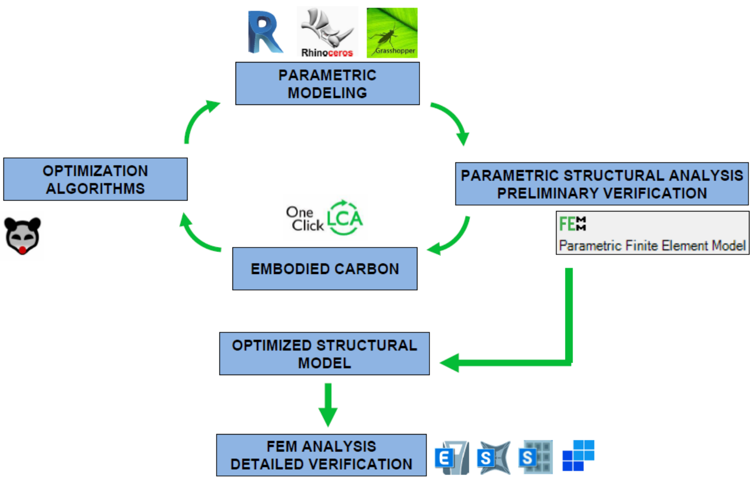

Figure 2: Optimization cycles - parametric approach

Step 8. A final detailed FEM analysis is performed to verify the given structure, and the results are provided along with the relative CO2 emission estimates.
Step 9. Based on the four assessment criteria (construction cost, room flexibility, use of own resources and CO2 emissions cut) a choosing-by-advantage approach (Suhr, 1999) is taken to perform the final assessment (see table 1). Hence, sustainability is included as a determinant factor in the final choice of the most advantageous alternative solution for the bearing structure.

Table 1: Choosing By Advantages table

	Post tensioned.	**pts**	**Bubble decks**	**pts**	**Hollow cores**	**pts**	**Wooden structure**	**pts**
Cost	2nd most expensive	4	2nd most expensive	4	Least expensive	6	Most expensive	1
Additional cost	*5%*		*5%*		***0%***		*15%*	
Flexibility	most flexible	6	2nd most flexible	4	2nd most flexible	4	Least flexible	1
Loss in flexibility	***0%***		*-10%*		*-10%*		*-40%*	
Own Resources	Max usage of Own Resources	6	High rate of Own Resources	4	No use of Own Resources	1	Low rate of Own Resources	2
Own res. used	***100%***		*90%*		*0%*		*50%*	
CO2 emissions	31%	4	29%	2	33%	5	34%	6
Variation CO2e	*-3%*		*-5%*		*-1%*		***0%***	
SUM pts		*20*		*14*		*16*		*10*
Advantages in	*2 criteria*		*none*		*1 criterium*		*1 criterium*	

In the table: Points are given from 1 to 6 (best); Relative advantage is given in relation to the best alternative for any given criterium (e.g., CO2e from Wooden structure is best, and post-tensioned structure is 3% higher emissions than that). The criterium "CO2 emissions" provides a percentage reduction in embodied carbon from the reference building.

From the choosing-by-advantages approach, the two most advantageous solutions appear to be the one based on hollow cores and steel, and the one based on bubble decks and steel.

The parametric analysis of a large number of these two bearing structure alternatives resulted in several estimates of the tons of CO2 equivalent produced by each solution. The values of the most optimal solutions for each alternative are reported in the following.

The first solution: Bearing Structure with post-tensioned slabs offered a CO2 equiv. the emission level of CO2e = 1525 ton (Embodied Carbon for lifecycle from cradle to site, stages A1 A3 and A4) see Fig. 3

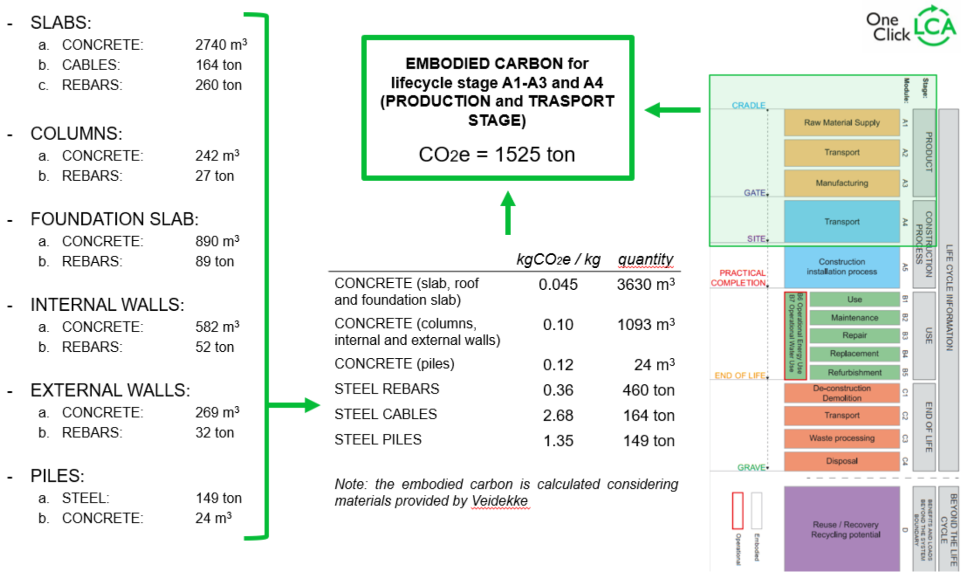

Figure 3: Alternative 1 - Post-Tensioned Slab – Embodied Carbon

The second solution: Bearing Structure with bubble deck slabs offered a CO2 equiv. the emission level of CO2e = 1056 ton (Embodied Carbon for lifecycle from cradle to site, stages A1 A3 and A4) see Fig. 4

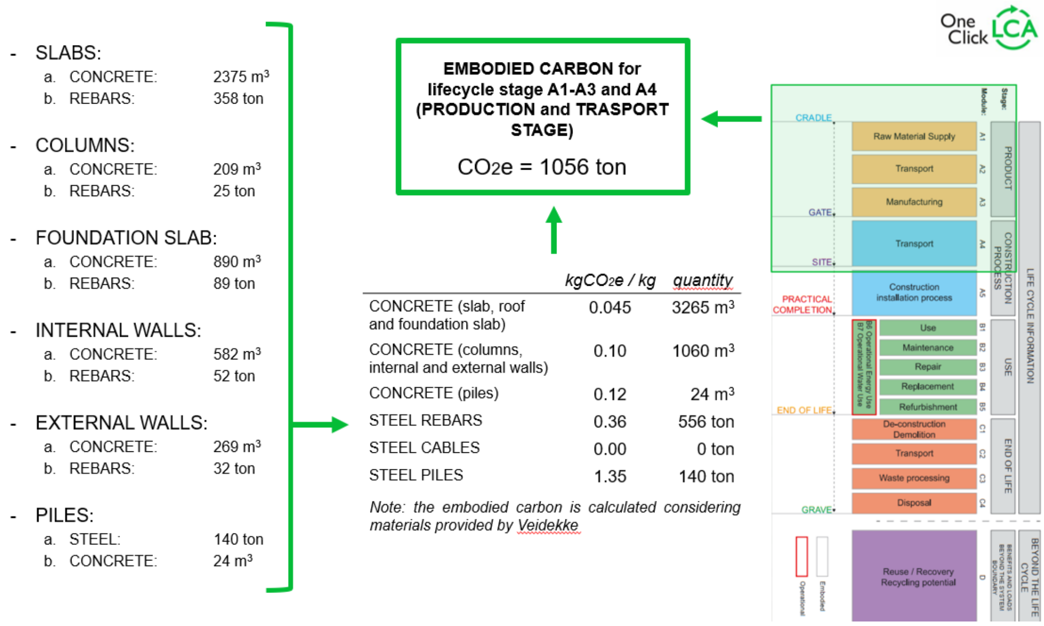

Figure 4: Alternative 2 – Bubble Decks – Embodied Carbon

The cases studied show that one solution, with bubble decks, has a significantly lower greenhouse emission level.

DISCUSSION

The findings show that the approach used in this project provides a powerful tool to elicit insights from the structural engineers in a phase that traditionally is the exclusive realm of project developers and architects.

During the planning phase sustainability target values are set up along with the classic project management cost, time, and quality targets. Already in the very early project phases, a parametric design approach can be used to determine which parts of the bearing structure can be considered as flexible and which parts shall remain fixed, as determined by the architects. The parametric model implements the variable parameters and runs the FEM analyses of the alternatives to yield optimized solutions that match the target values given at the outset. The parametric model is then used to run analyses of a large number of alternative structural solutions. Already at this early stage of the project development, parametric modeling is used to get insights into CO2 emissions levels. For each solution, quantity estimates of the greenhouse gas emission are provided for each alternative solution of the bearing structure. There is no theoretical limitation to the number of variants that can be studied.

Although the technology of parametric modeling enables these analyses at a very early stage in the design process, the core of the methodology rests within the set-up of the Target Values that steer the optimization process. Sustainability is therefore a choice made *a priori*, i.e. at the outset of the decision-making process. It is the owner of the sustainability goal, who takes the responsibility to set the sustainability targets. The investors may own the sustainability goal, as well as the general contractors. The latter will have to implement the targets in the construction process. In the case studied the structural engineer included embodied carbon calculations in their structural analyses. The designers, such as architects, engineers, and sustainability consultants need to contribute to the sustainability targets, by applying the right competencies to the design process. Although innovative and in line with the generic call to help in fighting climate change, the choice of giving sustainability such an important place in the design process does not appear as a simply idealistic one. The project uses choosing by advantages methodology to assure that while sustainability is taken systematically into account in a rigorous decision-making process, the other assessment criteria are given equal attention. The final choice includes sustainability considerations and reflects a larger spectre of assessment criteria.

CONCLUSIONS

The Veidekke HQ pro

ject shows that Target Value Design opens the door to including sustainability in the design process from the first phases of the project life cycle. This is in line with the principle of Lean construction, and yet this approach requires innovative technologies and rigorous decision-making methodology when sustainability is included among the goals of the project.

Advanced parametric modeling of the bearing structure makes it possible to analyze a large number of alternative structural solutions, in early design stages, and at a pace that makes it valuable to invest in such insight, for both investors and architects.

Getting this kind of insight requires therefore both the technical capability of running parametric structural models integrated with greenhouse emissions software, and the political willingness to break with traditional planning practices and let structural engineers "intrude" in the early project phases. The added value of this modeling approach is given by the high number of alternative solutions that can be studied at a very early stage of the design process. Provided that the project sets up a target value for the CO2 emissions, the design optimization process can be modeled accordingly.

The adoption of choosing by advantages decision-making system makes it possible to balance sustainability goals with other more classic objectives.

A systematic application of this method, structured and implemented as described, could change the design practices in the AEC industry and merge the fundamental principles of Lean construction with the ineludible needs for the sustainable development of our cities and infrastructure.

The limitations of this study are mainly related to the structural analyses of only two kinds of structures. Other limitations are those implicit in the kind of software that was used to calculate the structures and the CO2 emissions (e.g. precision of the optimization algorithms; the precision of the embodied carbon data of the materials and components adopted in the construction).

The results of this study could therefore spur further research efforts. The proposed approach could be repeated to study different kinds of bearing structures (e.g. including materials such as CLT or aluminum). The software used to calculate CO2 emissions could be further developed so as to include estimates of the impact on the project phases that were not included in this study.

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DEFINING CO_2 EMISSIONS OF A CONSTRUCTION PROJECT ON THE BASIS OF PROGRAMMATIC INFORMATION

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ABSTRACT

The environmental impact that a product has over its subsequent life is largely determined by decisions taken during the delivery process, i.e. defining needs for the product, choice of geometry, and choice of materials (Ashby W.R). Ashby's description is universal, covering all kinds of products. But if we make an interpretation to construction, environmental impact is due to

- programming process (needs for the product),
- massing during preliminary design (choice of geometry), and
- choice of materials during detailed design.

At the moment, CO_2 emissions are mostly defined from the use of materials during detailed design and construction, and from life cycle consumptions based on detailed design. In the detailed design stage, quantities of materials can be measured. And, as the mass of the building, internal conditions (e.g. internal climate) and external conditions (e.g. climate) are known, life cycle emissions can be modeled (or actually, calculated).

The problem is that this kind of approach does not involve a project definition or early massing during preliminary design to challenge designers to consider CO_2 emissions as they steer early design forward.

However, the most important decisions in relation to environmental impact are done during programming and massing in the preliminary design stage. If we set a question whether we need an auditorium or not, the decision made affects vastly more than latter decisions of the materials of the supposed auditorium. The need for an auditorium is not a design problem, rather it is a functional (i.e. programming) problem. And onwards, massing during preliminary design dictates the quantities of the materials measured later (more or less efficient massing, corridors, compact or scattered, more or fewer floors, etc). Longer distances between customer functions affect the quantities of staircases, external wall, air exchange ducts, cabling and site processes during construction in site (Pennanen, Ballard, Haahtela).

The authors argue herein that life cycle analysis (LCA) calculations should be used to help customers set goals, i.e., LCA should be used to steer design. Similarly, LCA should steer contractors and designers in detailed design. If CO_2 emissions are defined only from material quantities of detailed design, analysis is then rather declarative than helping to steer the design, as the calculation happens after the last responsible moment for programming and material selection.

This paper presents a theory and applications to involve the client and early design to proactive steering of CO_2 emissions during programming and early design; allowing all parties

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to collaboratively determine what CO_2 emission goals to set for a project as well as how best to achieve those goals.

KEYWORDS

Lean and green, Product development, value and design management.

INTRODUCTION

The question: "Do we need an auditorium?" cannot be solved by design. Showing a sketch with and without an auditorium does not provide more information to the actual question. Indeed, the answer to the question of whether or not an auditorium is needed is based on a customer's or users' functional needs. By contrast, the decision that a client or users need an auditorium, or they do not, has a large impact on CO_2 emissions during construction and over the auditorium's life cycle. In fact, the decision of WHAT to build is much more significant than a decision of HOW to build it (i.e., what is the frame structure of the auditorium, what kind of finishing, or what kind of air conditioning). Given the impact of the programming decision, i.e., the decision of WHAT to build, it is critical that designers, contractors, and clients understand steering.

And further, massing during preliminary design (i.e. three dimensional geometry defining how functions are located in the building) dictates internal distances, perimeters, projections etc. floor by floor, and thus dictates most of the quantities measured in detailed design (Pennanen, Ballard, Haahtela 2011), (Pennanen 2004).

Understanding this phenomenon, steering in programming and all design phases should be understood.

THEORIES OF STEERING

Theories of steering generally (not only for construction) are introduced under themes of managing complex systems. When construction is considered, complexity arises from different points of views of strategic leaders, operative managers, users, investors, and neighbors among others. And, if we ask for a sketch design from a hundred architects, we will likely get a hundred different solutions.

Theories of managing in conditions of complexity are associated, for instance, with "holism", "feedback", "cybernetics", "cellular automata" and "adaptive systems". Most of the modes of complexity management, especially when social systems are considered, are based on feedback and iteration loops, and assume closed loop production systems. Feedback and iteration loops consists', for example, of owners' wishes, measurement of consequences of said wish (money, time…), withdrawal from original wish, new proposals etc. In contrast to open loop systems, the output produced in closed loop systems is used to adjust or steer the system to its targets. That is done by measuring and comparing actual output to intended. (Simon 1996).

Construction project management requires purpose that are set in the very early phase before design starts. Goals can normally be derived from a customer's strategy. Goals can be addressed to

- functionality
- CO_2,e emissions
- costs
- time
- toxic emissions
- etc.

As the goals are multiple, the models needed to support decision-making should model, rather than one specific item, the entirety of the project itself. For steering, a digital twin of a building that spans over its lifecycle is needed. (Haahtela 1980).

CLOSED LOOP ITERATION

As construction is considered, iteration cannot, of course, be based on constructing buildings, demolishing them, and making better ones.

Steering and closed loop control requires modelling. BIM modelling is not appropriate for modelling customer needs, as those customer needs are its input information.

The environmental impact that a product has over its subsequent life is largely determined by decisions taken during the construction process, i.e. defining needs for the product, choice of geometry and choice of materials (Ashby 2013). Calculating costs in both emissions and currency is very similar. You multiply quantities of resources used by the unit cost, in currency or emissions, of using a single resource. Steering projects to goals for reduced carbon and other emissions should and can be added to the scope of project management.

BACKGROUND: STEERING FOR CONSTRUCTION APPLICATIONS

The Underlying theory of steering a construction project (Target Costing of a Construction Project) has been developed in Finland by professor Yrjänä Haahtela in 1980’s (Haahtela 1980). Steering is based on a target that is defined before a solution to fulfill the target (in any stage), and then verifying if the solution fulfills the target. If not, a new solution should be created. The target should not be defined by solutions to fulfill the target. E.g. target for proper design (spaces, timetable, building cost, maintenance cost) should not be defined by means of designing, but rather by means of programming.

Steering is possible if for a set of needs (a problem) there are multiple solutions to fulfill the needs. To a simple problem, such as $ax^2 + bx + c = 0$, steering is not needed, as there are two, one or no right answers (among real numbers). You must just learn how to find it. But if you ask a hundred architects for a solution to a single set of customer needs, you will get a hundred different solutions. And that will be repeated with engineers and even with planning the site operations. And before that with programming. The steering concept is aware that there is a big variety in design solutions for a single programming (as well as in programming solutions for a single customer functionality) (Haahtela 1980). It has been studied that there is a weak correlation between costs and architectural soft quality (Niukkanen 1980) among varying possibilities. It means that it is possible to set a steering range of costs of building to be narrower than the range of all possible architectural solutions without losing architectural soft value. And it can be done before design. By means of the concept, design can be steered in targets defined before the design has been started.

The steering concept was set in the early 1980’s and has been developed until now. Original application was based on spaces needed in programming (Haahtela 1980), and it was expanded to the actual customer functions in the early 2000’s (Pennanen 2004).

Steering a construction project in accordance with complexity management concepts is very simple in concept, though quite difficult in practice.

The steering process is based on:

- Defining the goal (functional, financial, CO2…)
- Rapid measurement of the proposed solution to provide the goal
- Analyses of whether the proposal meets the goal
- Rapid feedback to the actors creating the proposals
- Actions to minimize the difference between the goal and the proposal

- New measurement

Although the steering steps are simple, the steering problem arises from the difficulty to create useful information for management in a complex environment. Suh (2005) defines that a design system has a total amount of information that can be split into two groups, useful and superfluous information. Useful information relates solely to the satisfaction of functional requirement, whereas superfluous information does not affect the relation between the goal and design solution. To succeed, the main focus should be on useful information and superfluous information should be minimized (Suh 2005). If a doctor is asked when programming a hospital, whether he/she requires spatial support for surgery and whether he/she likes brick as a material in external wall, the former information is useful in programming and the latter is superfluous, because only the spatial support impacts the ability of the design to achieve the goal of providing a safe environment for patient care. As the customer and producer change throughout a construction project, so too does the language of usable information (owner or user for project management, owner or user for design, project management to design, project management to contractors, design to contractors). Thus, useful information must be studied through participants and project stages. The goal for the customer likely will not be the number of column footings and attributes of each footing, though these parameters will be useful information for the foundation subcontractor to meet their goal.

In a steering process, proper information is needed quickly and continually to provide management with goals, measurements and rapid feedback. In many cases, modelling is needed to create information (Haahtela 1980), (Pennanen 2004).

INFORMATION USED IN PROGRAMMING FOR STEERING CONSTRUCTION PROJECTS

Ideally, steering in project definition results in the following:

- All customers and stakeholders have expressed their business scope, needs and wishes.
- Business scope has been transferred to language that both the customer and the designer can understand, e.g., activities, spaces, performance.
- Customer knows the costs at completion and is willing and able to pay for the determined benefit and functionality.
- Customer knows the CO2,e emissions the project will create
- Customer is willing to launch the design process.

INFORMATION USED IN DESIGN

To understand how designing results in cost and CO_2 emissions, it is worthwhile analysing how designs that were initially very complex conceptual designs end in simple detailed manufacturing solutions. Design can be divided into two orthogonal perspectives (Pennanen et al. 2011):

- shape of the building and connections of the functions (concept design)
- building components (detailed design)

The design starts with solving the interdependencies (the connections) between the customer's activities and massing the building in its urban environment. There are numerous possible conceptual solutions for a customer's specification (and for the target cost), and the cost variability is vast. When we deal with concept design, the components, like cooling beams, suspended ceiling or details of external wall are normally not specified. Concept design can be understood as designing for the customer.

When the customer accepts the concept design, designers start to concentrate on determining the building components and materials that can be found in the market and sizing them (detailed design). It lasts until the construction is finished. Detailed design can be understood as designing for production and for the contractors.

Concept design determines the quantities of building components (in a single-floor building there is more roofing than in two-floor building, but fewer stairs). On the other hand, detailed design determines the unit costs of those components. The building cost and CO_2 emissions are a product of these perspectives: quantity times unit cost/CO_2 release.

INFORMATION USED IN LCA CALCULATION

The environmental impact that a product has over its subsequent life is largely determined by decisions taken during the delivery process, i.e. defining needs for the product, choice of geometry and choice of materials (Ashby 2013). Thus, Life Cycle Analysis calculation must cover helping the customer to set goals (project definition), steering designers (design) and steering contractors (construction).

If, during project definition, only valuable functions are determined to be built, the size of the building, and also its environmental impact, will be reasonable. Raising the utilization of the spaces by co-using them for many functions leads to smaller total floor area being constructed, which in turn leads to less emissions. Programming might be the most powerful tool to cut CO_2 emissions. In environmental thinking, less really is more.

During design and construction, the CO_2 emissions are due to production of building materials, transportation of the materials and site energy consumption. During the use of the building, emissions are due to energy use during occupation (heating, cooling, air exchange, energy of the user equipment, use of water…), replacing building materials (e.g. replacing heating unit after 15 years) and possible fuels to produce energy for consumption (oil, sun, water, biomaterials). How the building is demolished after use also affects CO_2 emissions. Recycling of the building materials lowers the lifecycle emissions that are caused by producing building materials (Ashby 2013).

LCA calculation requires steering, as target cost and CO_2 emissions values in Target Value Design. The problem is how to define a building level target and component level targets for steering and fast feedback. Otherwise, project teams will calculate what has happened, not what should happen.

In component level simulation the building level targets are assigned to the building components before start of design. Building components can be, for instance, external wall, cooling system, lighting system or nurse call system, material and work. Cost of the building product is easy to find for project management, but how to define the environmental impact of the building materials? There are statistics for most common materials. But more important, an Environmental Product Declaration (EPD) is a standardized way of quantifying the environmental impact of a product (verified in accordance with the ISO 14025). More and more of the producers of building material also inform about e.g. the CO_2 emissions released when producing the product. The project manager gets the cost and CO_2 emissions from the same source.

Innovations and development with modelling systems is needed to enable better steering of sustainability in construction. There already exist models that can support effective space planning and design in relation to business activities.

SIMULATION OF DESIGN AND CONSTRUCTION

Within Haahtela Group in Finland, the problem of various kinds of information concerning just the same building is solved by simulation of programming, design and construction (Haahtela 1980), (Pennanen et. al 2001).

Simulation is based on a fact, that clients, designers and contractor do their decisions in predictive ways, based on function.

The material /equipment use of an operation theatre is big. There is a plant room for circulation fans, ducts and HEPA filters. A 1000 lux lighting and tiling on the walls. Can all these materials and equipment be derived from the requirements of the function: limited particles in air (e.g. ISO5), hygienic surfaces? If so, they can be simulated from the function without designing. If we need a 1000 lux lighting, given assumptions on the lumen values of a luminaire fulfilling the functional requirements, quantities of luminaires can be simulated.

The basis to simulating massing arises from the spaces and function. For example, the need of natural light in rooms, the ability to access certain spaces from street level, and the possibility to locate a function in a basement. The city plan and its external requirements provide the framework for the massing.

The Simulation model uses programmatic information as initial information and results all building elements and components needed for desired functionality. It simulates decision making of real world architects, engineers and contractors. The simulated building can be considered as one possible solution among many others.

RESULTS OF SIMULATION AND COSTS

The literature on cost estimating is in general agreement that the level of accuracy of estimates increases with the specification (and eventually production) of the asset. The earlier the estimate in the life of the project, the lower its accuracy. Consequently, assessments of conceptual estimate accuracy are quite low. An extreme example: "…at this stage [prior to design], almost nothing is likely to be known about the building except its general size, and therefore it is pointless to go into detail about the cost before any designing has been done." (Ferry, et al., 1999). As a result of an incomplete specification of the asset to be constructed, the industry has historically accepted high levels of variance between the estimated and the actual total installed cost. Customarily, during pre-design, the industry has accepted a standard of +/-30 % of variance from estimates, after adjustment for changes in scope.

The previously described wide variance is based on projects that do not have proactive steering process with simulation of project delivery. With projects where proactive simulation has been used during programming and early design, the standard deviation of budgets before the design has been started compared to completed costs is less than 5 %. Thus, it has been shown that the simulation model and steering are powerful tools (Ballard, Pennanen 2013).

POSSIBILITIES TO STEER CO2 EMISSIONS, AS WELL AS COST, BEFORE DETAILED DESIGN

If programming and design simulation can successfully steer the costs of a construction project, it is possible to steer CO_2 emission, too. So that the customers decisions are in the front line, then designers, and finally procurement and construction in site.

In Finland, such simulation is in use, but, at the moment, researchers are lacking results, population of completed construction projects with simulation of CO_2 from early programming and design.

Researchers have made a study, calculating the correlation of costs and CO_2 emissions due to preliminary designs. The project was a day care center in Töölö district, Helsinki. The population was four preliminary design solutions. They were the best architectural solutions resulting from the competition. There were no bad ones, only good ones. One of them was built later.

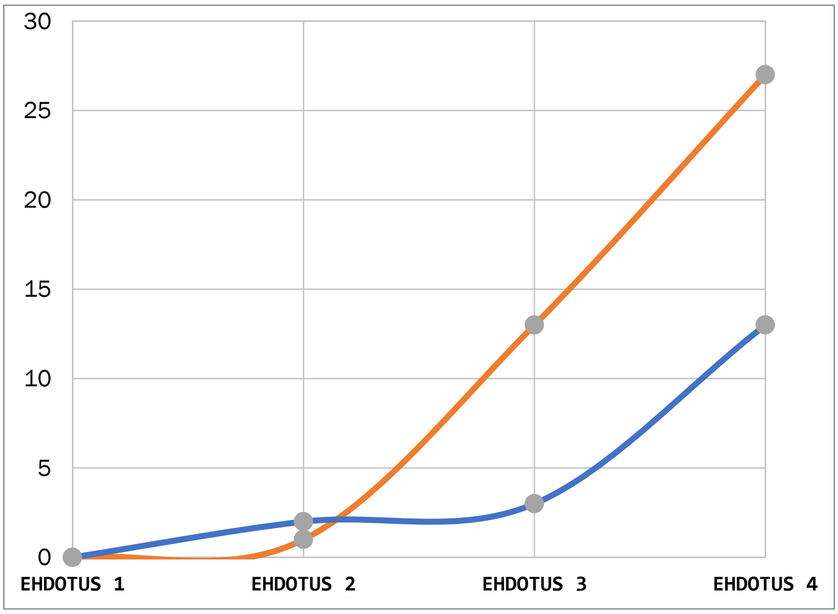

Figure 1: Four Architectural Proposals for a Single Programming of a Day Care Center. Blue curve: Cost variance of the proposals (%). Red curve: Variance of CO_2 emissions of construction (%) (Harvala A. 2022).

Ehdotus (Proposal) 1…4 are alternative design proposals for the same programming. Lower curve describes construction costs (0…13 %) and upper the CO_2 emissions of construction (0…27 %) (Harvala A. 2022).

The first conclusion (based on very low population) is that variety among proposals is high in relation to costs and CO_2 emissions (that was supposed basing previous research). Variety of soft architectural quality in this population is low, as the best four proposals are considered. The phenomenon is a subject of steering, from programming to the use of the building! As the correlation between costs and CO_2 emissions is strong, the researchers suppose that the proven methods to steer costs can be applied to CO_2 emissions.

In conclusion, simulating and steering projects from their earliest stages allows stakeholders to consider and actually change the environmental impact of the construction before the realization of the emissions. While costs in building projects have been considered this way for longer, they mainly impact only the stakeholders themselves. The emissions, however, impact the entire planet. It would thus seem prudent to utilize simulation and steering in project management, for both costs and especially CO_2 emissions.

FUTURE RESEARCH

Simulating CO_2 emissions from programmatic data has just begun. The investors get information of CO_2 emissions before design, based on their decisions. And later based on the designs as well.

Researchers need more evidence from on-going projects. It seems that it can be provided.

On the other hand, life cycle emissions are not included in this research. The simulation model, as used for predicting function and massing, is also capable to steer life cycle emissions. That is the issue of another paper.

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ON-SITE WASTE MANAGEMENT: A USE CASE OF LEAN CONSTRUCTION AND ARTIFICIAL INTELLIGENCE SYNERGY

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ABSTRACT

The construction industry generates more waste than any other industry. Waste management is getting more and more attention as the policies and mentalities evolve to face the challenges ahead: climate change, materials shortage, circular economy. Most of the waste management activities consist in waste sorting and is carried out downstream of the construction execution, resulting in lower material recovery performance. This paper proposes a method to segregate waste (separate waste based on how it is created) to enhance the reuse, recovery, and recycling of construction waste. Therefore, it investigates the applicability of Lean Construction methods and Artificial Intelligence (AI) tools and their potential synergy. Directly applying classical waste management AI tools (as used in recycling centers) was tested based on real case data. It required an excessive need for data and training. Alternatively, a Lean Construction framework based on a combination of the 5S method, and the Takt Time Planning method was proposed. It enables the streamlining of flows in order to mitigate the impact of on-site constraints on AI training. We instrumented this Lean Construction approach with an AI tool that checks the quality of the construction waste segregation process by detecting mixed materials in dumpsters.

KEYWORDS

Lean Construction, process, sustainability, Artificial Intelligence, waste segregation.

INTRODUCTION

Inspired by the Toyota Production System, Lean Construction aims at a systematic reduction of wastes within the production processes related to construction. To be applicable and relevant for the construction sector, the original list of seven wastes from Ohno was supplemented based on the Transformation Flow and Value theory of production (Bølviken, 2014). In addition to the original time losses, Lean Construction also put emphasis on material losses and value losses. Material losses, consisting of Excess Inventory and Scrap waste (Ramaswamy, 2009) have indeed been highlighted as a major problem for the construction industry (Formoso, 2002).

Reducing material wastes in construction is also a major concern outside of the Lean Construction Literature because the tremendous amount of CDW (Construction and Demolition Waste) has a tremendous environmental impact worldwide. For example, in France, CDW represents 70% of the total waste (Ademe, 2021) and 30% of total waste produced worldwide

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(Papargyropoulou et al., 2011). On average, more than 35% of CDW will and up in landfills annually (Menegaki and Damigos, 2018).

As an answer, Construction waste management processes aim at identifying, reducing, reusing, and recycling materials generated during construction to minimize their negative impact on the environment and turnover (Olabode, 2019; Esin and Cosgun, 2007). However, there is a lack of data about the handling costs of waste to drive companies towards more significant effort and investments, and notably to justify the investment on dedicated technologies. Moreover, positive incentives, such as labels and good brand image, as well as negatives, such as taxes or penalties, are not compelling enough to support diversion of CDW, and a more efficient regulatory framework and public incentives are needed (Purchase et al., 2021).

Most practices and research in the C&D Waste Management research and practice are based on a "3Rs" principle, which refers to reduce, reuse, and recycle and establishes a classification of the actions related to Waste Management arranged according to their impact to the environment (Peng, 1997; Kazerooni, 2012). Further possible "Rs" have been proposed, but an overarching principle remains to prevent as much disposal as possible: waste that cannot be reused or recycled, will most likely end up being burnt or landfilled (Nagapan, 2012). All material waste that cannot be reduced should be kept reusable or recyclable, which requires separating the various types of materials. Considering the climate emergency, recent regulations put a growing emphasis on these principles while becoming more compulsory. For instance, the revised waste management law in Luxembourg compels construction companies to sort 7 types of materials during the execution phase: wood, inert materials, metal, glass, cardboard, plastic, plaster, and hazardous wastes (Ministère de l'environnement, 2022).

For a construction company, such new regulation implies extra cost for sorting scraps in the mixed waste dumpster or being able to handle separate flows for material wastes. In both cases, the added costs or activities fit within the Lean taxonomy of waste (Bølviken, 2014) and should thus be considered from a Lean Construction perspective.

Therefore, Lean Construction might answer some of the barriers to on-site sorting strategies highlighted by Bao et al. (2019). However, the Bao study also points out a lack of technological solutions. In other sectors, such municipal waste management, sorting is performed by technologies based on Artificial Intelligence (Lu and Chen 2022). The use of such technologies in construction is a topic of growing interest, as it relates to their applicability for material waste management in construction.

More recently, the interplay between Lean Construction and AI have been studied from a theoretical perspective by (Cisterna et al., 2022). The authors highlight the potential for synergies between LC and AI: material waste management might be one of these.

This article will investigate the applicability and synergies of Lean Construction and AI for the purpose of reducing disposal on construction sites.

BACKGROUND

Assisting waste management through AI is uncommon in the construction industry, even as the use of intelligent computer-vision seems very promising for object sorting tasks. Early ideas date back to 2000 (Mattone et al., 2000). Most of the waste management solutions appear downstream of the execution phase, with recycling robots (Lukka, et al., 2014) and especially in recycling centres. A lot of facilities are equipped with conveyors and robotic arms to sort waste though in some cases the sorting is operated by humans. A challenge for waste sorting derives from the fact that many wastes are already mixed, and some are difficult or impossible to separate (for example, coating with plastic and metal); this type of waste will most likely end up being burnt or serve as landfilling.

A different approach lies in the segregation, where waste is separated into dedicated containers as it is created at the workstation; this eliminates the need for later sorting activities. This approach is common in sectors like municipal waste or household waste (Lu et al., 2022) where AI-based waste segregation is performed in closed dumpsters with image recognition algorithms and automated segregation. This reduces human intervention and error by leveraging a tool able to complete segregation. However, use of such tools is made possible by the relative homogeneity and small size of the waste; moreover, these tools can usually manage only 3 types of waste (paper, plastic, metal) and are not suited for bulky and dense material. Thus, the direct applicability of such technologies is very limited in the construction sector.

Recent work (Lu et al., 2022) demonstrated the identification of precise waste elements (i.e., known as semantic segmentation) to help with the segregation and precise identification of mixed wastes. This technique may be suitable in a construction site's context though the specific training of the AI model should be adapted for a construction site's needs and operational contexts. Indeed, semantic segmentation is quite a complex AI model that requires a lot of training and that may be less robust in construction because of the variety of situations on site.

Moreover, if that kind of approach seems efficient from a technical perspective in a specific evaluation case, the role of the humans involved is not sufficiently considered, which may be particularly inadequate to construction as highlighted by Noueihed and Hamzeh (2022). Therefore, a practical waste management process, encompassing the whole waste management is needed to ensure its applicability in construction.

Regarding Lean Construction approaches, the 5S method has already demonstrated its capacity to reduce material wastes and losses of control on material flows by maintaining clean and tidy workspaces (Berroir et al., 2015), and seems thus, applicable for waste segregation. However, authors also showed that 5S should not be applied dogmatically and in isolation but combined with flow identification and management methods to streamline flows, facilitate change management, and make improvements last from project to project. Hence, a waste segregation process based on several Lean Construction tools should be proposed.

This article assumes that waste segregation should be preferred to downstream sorting. The current AI methods listed above are not encompassed in any Lean process, and thus, they may be difficult to apply in the context of CDW segregation on site. This paper will focus on enabling CDW segregation based on intertwined Lean Construction and AI.

METHODOLOGY

To investigate the applicability of AI for waste management in the specific context of construction sites, we propose to follow a Design Science Approach (DSA). The grounding of our proposition is based on the aforementioned background work on AI and Lean Construction and their related limitations. The DSA proposed artifact is a Lean Construction process encompassing an AI tool for waste segregation and it will be compared to an approach based on AI only (similar to what is applied in other sectors). The solutions will be evaluated according to the amount of data needed as well as the feasibility of the training, maintenance, and update of the AI model. Accordingly, the research was split in 2 cases:

Case n°1: AI tool without Lean

This case is based on current practices of AI implementation and training in other sectors. Research protocol consisted of:

1. Data collection from 2 construction sites in Luxembourg
2. Training of the algorithm
3. Evaluation of the amount of data and training time for an implementation on site.

Case n°2: AI tool integrated in a Lean Construction process

Considering that AI alone is not a "silver-bullet" solution to solve on-site waste segregation, this case investigates what Lean process could be applied and how it can integrate with the development and implementation of an AI solution for onsite waste segregation. The authors sought to address two questions:

How can LC enable the integration of technology in the segregation process? (Q1)

How to train and maintain an efficient AI model for on-site waste segregation? (Q2)

Subsequently, the research was conducted as follows:

1. Proposition of Lean Construction process for waste segregation on site with computer vision (using planning data from the second pilot site cited in case 1)
2. Development of a computer-vision AI model (visual waste recognition).
3. Test of first round training in controlled conditions
4. Evaluation of the amount of data and training time for an implementation on site.

A third case, "Lean process without AI," is not considered here because literature already established that such a solution would be applicable. This case needs to be studied in future research from a performance and efficacy perspective.

RESULTS

CASE N°1- AI TOOL WITHOUT LEAN

The first case was performed through the data collection of waste on two construction sites in Luxembourg. Cameras were installed near waste collection zones, above dumpsters and enabled to take one (1) photo every minute, collecting more than 25000 pictures overall. From an AI perspective, the training environment was uncontrolled (dust in the air or on the material , water, snow, overlapping materials).

These dumpsters were supposed to collect only one type of waste. However, a lot of wastes were mixed (plastic with wood, metal with plastic, plastic bags with various waste inside). Training an algorithm to identify various type of waste in such a context resulted in a time-consuming labelling phase. Half of the data was totally unsuitable for exploitation because scrap was too mixed or hidden inside plastic bags (see fig.1). In the other half of the photos, materials were altered (e.g., wood was contaminated with paint or oil) as well as overlapping materials created errors in the AI training, as did variable conditions (lighting modification, rain, snow).

Figure 1: Example of dumpster pictures used to train the model

As a result, the training time was over 200 hours, and the recognition rate was below 60%. Accordingly, implementing such an AI tool on a construction site would require training and updating the model several times during the project, as the material flows evolve. Hence this method is not robust nor suitable for replication.

CASE N°2 AI TOOL INTEGRATED IN A LEAN CONSTRUCTION PROCESS

How can LC enable the integration of AI in the segregation process? (Q1)

Dealing with messy and overcrowded workspaces is the goal of the 5S method (e.g., Berroir et al., 2015). Aligned with 5S, segregation requires to identify materials flows exiting the workspace and to be able to keep them separate as much as possible. A limitation reported during the data collection on site was the use of many plastic bags and the mixes of scraps. It was reported from the pilot projects that most of these materials were already mixed at the workspace. Small piles of materials left at the workspace rapidly tended to become mixed chunks of wastes. Separating such waste from AI automatically is nearly impossible, and the resulting waste are costly as they end up in disposal. Moreover, companies on site usually rejected the responsibility to clean up for each other, meaning that un-segregated piles of waste were challenging to process, as no one contractor had responsibility for clean-up and segregation. Hence, applying a 5S method would contribute to waste segregation as reported by Leino (2014). Main expected benefits are reported in table 1.

Table 1: Expected contribution of 5S to waste segregation on site

1st S, Sort	Systematic elimination of unused material before they get mixed
2nd S, Set in order	One place for each material
3rd S, Shine	Visual workspace: systematic cleaning, any leftover pile is visible as an anomaly
4th S Standardize	Adapted equipment (bins and container) and rules at company level
5th S, Sustain	Rigorous application of standards and inspections

Accordingly, the implementation of 5S appears highly beneficial for waste segregation, but as shown by Berroir et al. (2015), its implementation and maintenance over time greatly benefits from other Lean Construction methods. Methods that enable balancing and identifying the flows of material would enable identifying and adequately sizing the equipment required to collect and carry the waste. Such an approach was proposed by Heinonen and Seppänen (2016), learning from examples from cruise ship cabin refurbishment, they suggested improving takt time application in construction by explicitly considering logistics and garbage collection at the planning level. In practice, they proposed to implement garbage collection points but practical implementation in construction and location of the collection point was left for future study. Consequently, based on the case of the second pilot projects involved in this research, we considered several setups for such collection points.

A single "one-fits-all" setup of waste collection point would need to be suitable for segregating all types of waste generated from every task performed in the work zone. Enabling this type of collection point would require a lot of equipment since one collection point would be needed at every floor where there is some work and since the collection point should be composed of all the different containers. This option might often not be applicable for space reason, it might strongly increase costs. The opposite approach would be to define individual containers for each team with the appropriate equipment for their various waste streams. This approach might also require excessive amount of equipment since many waste streams are common to several trade and could be mutualized. Additionally, it would require workers to move all the equipment with them, which should be avoided from a Lean Construction perspective as it appears as a new time loss for the workers and is particularly not suitable in cases where they may have work in progress on several zones at the same time. Moreover, the collection of the waste by a logistic operator would require additional capacity. Lastly, this setup does not really take advantage from balancing and identifying flows of material in the way that Heinonen and Seppänen (2016) documented and would in practice look very similar to a case where everyone is managing its own wastes. Consequently, the proposed solution for this case n° 2, is to take advantage of a "takt timed" planning to find a balance between these 2 setups and to define collection point based on takt phases as for example in figure 2.

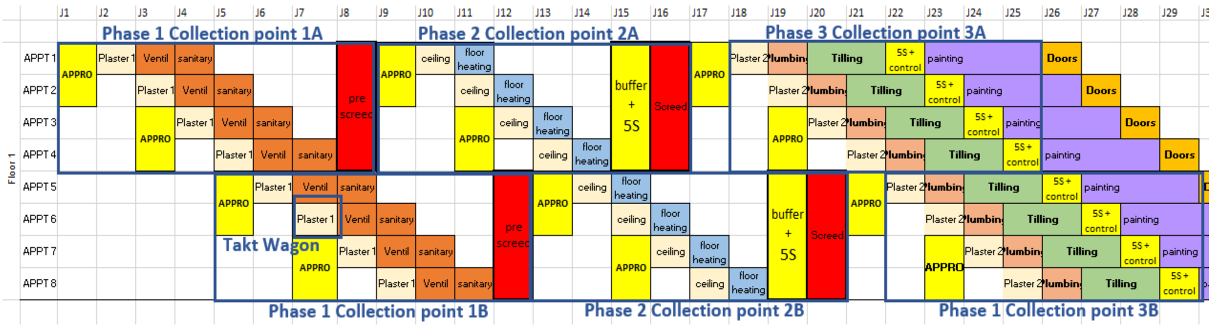

Figure 2: Example of takt timed planning extract with visualisation of the collection points

More precision on the tasks can be found on table 2, but the details of this planning is of little importance since this example only aims at illustrating the idea of defining and sizing Collection Points based on takt phases. Typical level of details of a takt times planning enables explicit consideration of deliveries and cleaning (highlighted in yellow in fig. 2). This example presents a group of tasks in different takt zones circled in blue and referred to as "phases". Implementing waste collection points at a "phase level" would result in 3 different setups of collection points, each one following a group of trades.

In this scenario, a phase encompasses half the apartments of a floor, meaning that each collection point would have 2 instances (e.g., Phase 1 "A" and "B") intended for the same flows. Thus, workers would always have access to the right container at the floor where they are supposed to work. This level of detail allows to anticipate the kind of waste managed at each collection point as illustrated in table 2. This list is not exhaustive but intended to show that material waste flows can be identified individually at the level of each collection point based during planning. Furthermore, the application of the takt time method would result in more stable amount of waste generated, thus allowing construction managers to select waste containers with the required shape and capacity.

Table 2: Identification of potential waste types at each Collection Point

Collection point	Tasks	Type of waste
CP1	Plaster (1st layer) Ventilation Sanitary Pre-screed	Plaster, Aluminium (rail), packaging plastic, pallets, Gravel, wood, tubes, cardboard
CP2	Ceiling Floor heating screed	Plaster, Aluminium (rail), plastic packaging, polystyrene, plastic tubes, pallets, Cardboard
CP3	Plaster (2nd layer) Plumbing Tilling	Tilling, Plaster, Aluminium (rail) Pallet, cardboard,
Out of CP (collected directly by subcontractor for each task)	Painting Doors Electrical	Paint can, plastic packaging, electric wire, gravel,

To ensure waste collection at each task/takt wagon level, teams should be equipped with small individual containers (e.g., big bags or rolling dumpsters) as presented in step 1 of figure 3. Material can be then brought to the collection point where containers can be equipped with cameras and a visual recognition tool trained for the relevant containers and types of wastes, as represented in figure. 3.

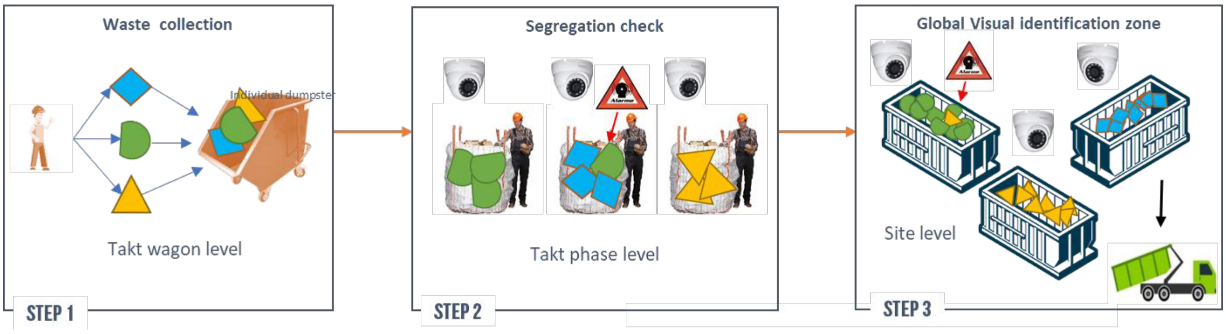

Figure 3: AI supported waste segregation process

Compared to what was performed in case 1, the waste collection points operate at an intermediary level in the management of waste flows; the control device prevents mixing of wastes, supporting "clean containers" (one type of material per container) onsite. A last control, Step 3 of Figure 3, is based on larger dumpster observation by camera. This uses a similar AI approach with different training data as the large dumpster situation is different from the small "local" dumpster situation. The large dumpster can also be a last quality control point for downstream waste recovery (even if it goes beyond our approach) to prevent costly mixed waste from leaving the jobsite. Contrary to classical "waste recovery" activities performed downstream of the execution phase, the LC framework proposed allows project teams to streamline material flows, perform waste segregation on site, and reduce the impacts of environmental constraints that hindered the applicability of visual recognition on the construction sites.

How to train and maintain an efficient AI model for on-site waste segregation? (Q2)

The key to the success of this solution is the visual recognition system that can detect and characterize each material despite the constraints of an uncontrolled environment (the construction site): dust (in the air or on the material), water, snow, or contaminated materials (painting or oil covering a part of the material). Another key constraint will be the overlapping of materials when the dumpsters will be emptied into larger dumpsters or big bags. In many cases, the materials can be partially or fully hidden from the camera.

The solution is based upon in-situ data (photos) that rely on the trained AI models introduced in the previous section. This AI, notably its training and maintenance, comes with a cost that downstream waste recovery will not face. However, it directly puts the responsibility to the person producing the waste whilst facilitating their success is the sorting of their waste (by directly providing adapted containers and explicit zones). A simple set-up was selected for the waste recognition and segregation AI model. To do so, a camera was set on top of a big bag/dumpster deployed on site. This camera helps to capture waste drop activities as soon as they occur. Indeed, the wastes are supposed to be dropped in the correct container (big-bag or dumpster). As shown in Figure 4, the technical process is articulated as follows: 1) the camera detects an activity. This step is required to avoid having a continuous execution of the waste recognition model; indeed, the model should only run when waste needs to be detected in order to reduce the energy demand from the AI system that is likely running off of batteries. 2) In a second step, the model is executed on an embedded device (e.g., a Jetson Nano card). It tries to detect the waste being dropped and whether or not this material is correct for the container (e.g., putting only wood in the wood dumpster). 3) In a third step, the algorithm warns the personnel about the correctness of waste segregation or alerts if a mix is detected, and it creates a log that keep a trace of the current detection. This trace can be used later to know if there is still mixed waste in the container, to know where it is, or to identify false positive cases that can be used for future training of the AI model.

A simpler AI approach than the one described in (Lu and al., 2022) was selected, since it's important to have: 1) a human in the loop, and 2) more robustness for recognition and thus less training. As a result, the training relies on multiple simple classification models. Each of them identifies the presence of a single material in the image captured by the camera. If more materials are recognized, then a mix is detected.

An important step of any deep-learning model is the training, mostly based on the extension of a pre-existing recognition model. Indeed, most of the recent approaches extend (i.e., use transfer learning) an already trained model based on daily-life objects (e.g., boats, cars, bananas, ducks, etc.). Basing the training on pre-trained algorithms drastically reduces the number of required photos.

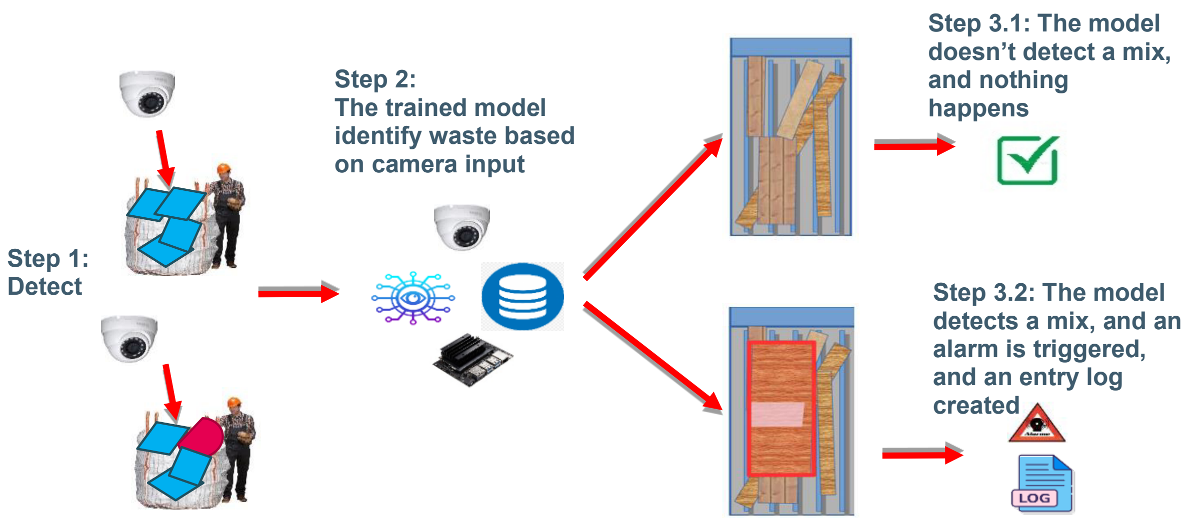

Figure 4: The waste identification technical process

Moreover, following the same principle, the training of the models has been started in a controlled environment (laboratory training; see Figure 5), with 4 basic materials: wood, metal, plaster, and bricks. It consists of around 550 images of the basic material and 550 images of the basic materials mixed with others. The concept of the first round of training was to have an already sturdy model before deploying it on-site but also diminish the quantity of data needed to train the algorithm. Certainly, training the algorithm directly with on-site data would require at least 10 times as many photos, as discussed in other studies (Lu and al., 2022), and it is very likely to face a lot of peculiar cases, thus disturbing the learning phase. Starting the training in a controlled environment allowed good recognition results (above 90%) of the 4 basic materials with fewer data.

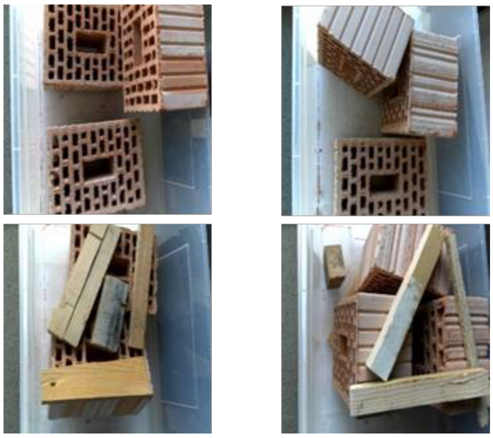

Figure 5: Lab training sample: two upper photos brick not mixed; the two lower brick mixed

Once the results are confirmed in the laboratory, a second round of training will start on-site, with constraints (lightning modifications, dust, rain, overlapping materials, contaminated materials) to strengthen the algorithm and have a fully functional tool. This training phase will be longer since it is expected to have more mistake occurrences due to the on-site constraints weakening the algorithm's performance.

Since such AI model cannot be 100% effective, we will have to introduce 2 "bypass" buttons. The idea of those buttons is to make the system robust according to the site or construction company specifically without blocking or keeping mistakes in the automated part of the segregation process. As illustrated in Figure 6, the two buttons will help with the identification of the false positive and the false negative solution (i.e., mixed, or not mixed wastes). These bypass buttons, called "force push," will be used in case the models make a mistake. For example, the model detects a mix but there is no mix, the "Force NO MIX" button will be pressed to notify that the model made a mistake, and, hence, will learn from the mistake.

In the other case, a mix is not detected by the model, the "Force MIX" button will be pressed to notify an error, and the model will hence learn from that mistake.

If a mistake is recuring, the training will be extended through the identified wrong situation to make the system more robust. More experiments will be needed to implement a correct pace of training when there is sufficient data to make another training.

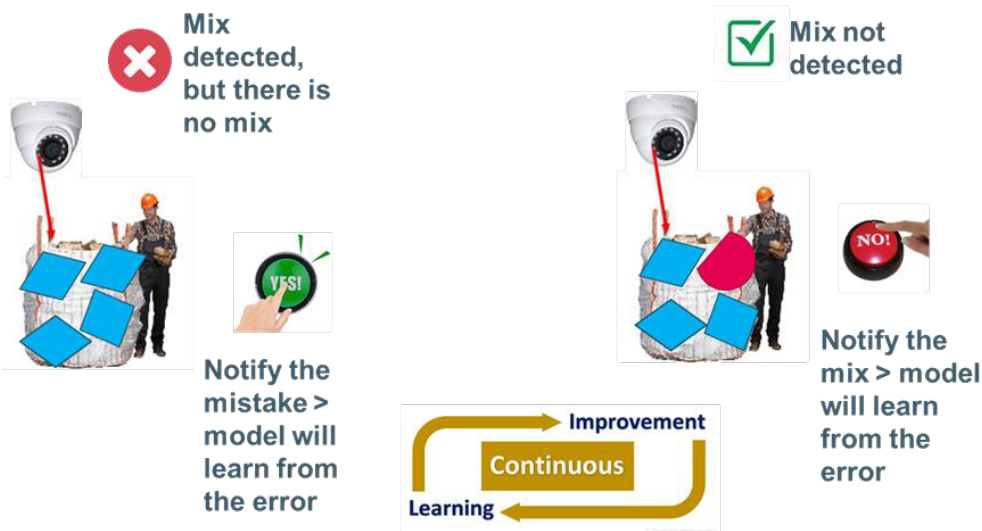

Figure 6: Notification buttons on site of false-positive and false-negative with continuous learning

As a summary, a set of simple trained models is operating, and it detects the presence or absence of each individual material on a camera. It is based on in-lab training that is enhanced with on-site image training. The results of those models are then crossed together to state if there is a mix or not. It is also vital to allow for tracking and reporting incorrect classification to enable the model to learn from the site or construction company. The idea is to be able to learn from errors to ensure a more robust detection.

DISCUSSION

The Lean Construction framework proposed in this article might be applied without the AI control tool, but with a human supervision. Further research could thus compare the Lean Construction + AI framework proposed here to a Lean Construction without AI solution according to their respective performances in real case conditions. Showing the benefits of the AI integrated solution would prove the synergy between Lean and AI for the use case of waste management on construction sites.

The explicit identification of deliveries and garbage collection in the Takt Time Planning, as illustrated in this paper, can contribute to further reductions of environmental and economic impacts of the construction sector based on the application of Lean Construction techniques. Hence, it would contribute to merging upstream (logistics) and downstream material flows (garbage collection) similarly to what is presented by Heinonen and Seppänen (2016) in the context of ship cabin refurbishment. The implementation of garbage collection would allow a third-party logistics operator performing Just-In-Time deliveries to easily collect the scraps and return them with their current (standard) vehicle, achieving an integrated reverse logistics chain and reducing the impact of transport. Further development of the AI tool may also integrate quantity estimation and forecasting to better identify when collection points should be taken off, and in what priority. This may also contribute to collecting more data about the waste generated on construction sites to provide policy makers with quantitative data from construction sites that supports defining and implementing new environmental policies.

CONCLUSION

This paper introduced an instrumented AI based process dedicated to waste segregation on construction sites. To do so, a first experiment was conducted to train an AI model without a Lean approach; it resulted in a time-consuming training and showed insufficient performance. Indeed, this first experimentation forced us to face all the on-site constraints at once, resulting in: (1) a time-consuming labelling phase for AI training (requiring a lot of data) and (2) a more complex AI approach (semantic segmentation).

The complexity of the problem can be lowered by identifying and streamlining material flows using Takt Time planning and 5S, offering a proper framework for the waste segmentation process that mitigates the on-site constraints. A simpler or more reliable AI model can thus be used, with shorter training time and less required input data.

However, the AI tool presented here is not fully functional since it has not been trained nor tested yet on a construction site, so it has yet to confront the "noise" of the environment (lightning modifications, dust, rain, overlapping materials, contaminated materials). This second round of AI training will be the core of the future work to be carried out on the tool as well as its integration on various construction site typologies.

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ROLE OF WORK FLOW IN REDUCING LIFE CYCLE ENERGY CONSUMPTION IN CONSTRUCTION

Musab Jamal Maraqa[1], Rafael Sacks[2], and Sabrina Spatari[3]

ABSTRACT

Lean construction aims to improve the construction industry by focusing on flow and value and eliminating waste. Reducing waste can also meet environmental goals by reducing greenhouse gas emissions (GHGs) and improving environmental performance. Many green building rating systems have emerged over the last three decades as instruments to incentivize the production of buildings that minimize the impact on the environment and human health. However, those approaches are oriented toward the end product only, leaving builders without guidelines on effective processes to reduce operational waste. This research reviews and evaluates opportunities to mitigate GHGs and improve environmental performance through lean construction. It measures the effects of lean principles on reducing GHGs by improving the flow. Case study research was used to measure the quantity of diesel used for heating two construction projects in a cold climate; one is a traditionally managed project and the other is managed using Virtual Design and Construction (VDC) and the Last Planner System (LPS). Results show that the floor cycle time reduced from 189 days to 115 days in the lean-VDC project, a reduction of 64%. Also, the total embodied GHGs reduced from 1,037-tons CO_2e to 629-tons CO_2e, a reduction of 408-tons CO_2e.

KEYWORDS

Lean construction, life cycle assessment (LCA), energy consumption, flow, transformation-flow-value

INTRODUCTION

The construction industry is responsible for a significant amount of energy consumption and greenhouse gas emissions (GHGs) (IEA, 2019). Construction waste in Israel represents major source of waste. It contains different construction materials like steel, blocks, tiles, plastic materials, gravel, and soil (Katz and Baum, 2011). In 2016, the amount of construction waste rose to 7.5 million tons, (Tal, 2016).

Lean construction aims to eliminate different types of wastes by focusing on flow and value. Waste in construction, understood from the lean point of view, comprises not only physical waste but any exhaustion of resources that does not satisfied value to the customer (Womack and Jones, 2003). Bølviken et al., (2014) studied the wastes in construction from the Transformation-Flow-Value theory (TFV) point of view. They proposed a definition of waste

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as the use of more inputs than needed and unwanted output. This definition can cover aspects inside production, including exhausting more than is needed and to producing unwanted things. They classified the transformation waste as physical material waste, non-efficient use of material, and non-optimal use of machinery, energy, or workers. For the flow waste, they mentioned waste in the workflow and the product flow. Workflow waste includes the unnecessary movement of people, waiting and inefficient work, while product flow waste includes, materials not being processed, and unnecessary transportation of material. Finally, for the value waste, they classified them in two waste categories: main product and by-product. The main product waste is lack of quality and intended use. By-product waste consists harmful emissions or injuries and work-related sickness.

Green building rating systems aim to provide healthy facilities, designed and built in a resource-efficient manner (Kibert, 2007). According to Robichaud and Anantamula (2011), there are several pillars of green buildings: the reduction of environmental impact, the increase of health conditions of facility users, the economic returns to investors, and the total life cycle impacts on the project phases. There are different green building rating systems that are well known. These rating systems aim to take a holistic perspective on a building's full life cycle. Yet, there are gaps in how these rating systems capture all processes within the cradle-to-grave context of buildings.

Many researchers studied the effects of lean construction on reducing construction waste and improving environmental performance. Saggin et al. (2015) examined the relationship between lean and LEED in a case study. They calculated the amount of physical waste reduced in a LEED-certified project managed using a lean management approach. They calculated the total volume of waste and normalized it by square meter. Results show that the waste was reduced from 13.53 cm/m^2 in the traditional management project to 10.93 cm/m^2 in the lean project, a reduction of 20%. Koranda et al. (2012) studied the integrity of lean construction and sustainability in six different construction projects in the Midwestern United States. They used qualitative methods, interviewing project managers to identify the waste sources for sustainability and lean. They concluded that sustainability practices result in reducing physical waste generated during construction which lean also aims to eliminate. However, they identified several differences between the two concepts. Lean construction aims to eliminate the different types of physical, process, and operational wastes, while green building rating systems like LEED and BREAM focus on reducing physical waste.

Maraqa et al. (2022) studied the effect of lean construction in minimizing physical and operational waste. The researchers studied three construction projects with different management approaches. One was managed traditionally, the others were managed using VDC and the Last Planner System. The researchers analysed the partition wall activity since it represents one of the main finishing activities during the construction phase. They found that the embodied GHGs in the lean-VDC project per meter square of partition area were 12 kg CO2e/m^2 compared to 58.4 kg CO2e/m^2 in the traditionally managed project. The reduction of GHGs in the lean-VDC project demonstrates the potential of lean practices in improving environmental performance. A further study examined the effect of lean and VDC practices in improving the process and reducing associated operations waste (Maraqa et al. 2021). The researchers monitored block worker activities and divided them into value-adding and non-value-adding activities. The results showed that lean and VDC implementations raised the value–adding activities to 68.4%, compared to 35.8% in a traditional project.

Other studies measured the effect of lean implementations on improving process and operation flow in construction. Maraqa et al. (2021) studied the role of implementing BIM and lean to improve the flow in eighteen construction projects with different combinations of management approaches. Based on a 10-point scale, their results showed that lean and BIM implementations improved the workflow to 8.12, compared with 4.91 in projects that implemented traditional management. However, this study measured the impact of lean and BIM in improving the workflow from a management perspective without considering the environmental impacts.

Green building rating systems have been criticised because they do not address the environmental problems across the life cycle of a building, and for their transformational checklist approach, which lacks a methodological basis for efficient implementation of green practices during the construction phase. Carneiro et al. (2012) claimed that green building rating systems like LEED does not allow the flexibility valued by lean construction, and it recommends the implementation of environmental interventions without concern time and cost minimization. They argue that while LEED and lean construction practices contribute to the pillars of sustainability, since both focus on the waste elimination concept, the two methods differ in their application. Other researchers claimed that there are some contradictions between green building rating systems and lean construction practices. In some cases, implementing lean construction practices such as the just-in-time delivery concept can consume more energy sources and emit GHGs (Green, 1999).

The objective of this research is to evaluate the potential for improving the construction workflow and reducing the project cycle time in cold climate areas. The research analyses two hypothetical projects with different management approaches: traditional and lean management. Also, three scenarios - Original, Process (location flow) optimization, and Operations (crew flow) optimization - were modelled to evaluate the amount of energy consumed in each, which helps the project manager make better decisions in managing the sub-contractors to guarantee the achievement of general optimization rather than local optimization. These decisions can have an adverse impact on the amount of GHGs emissions resulting from the project during the construction phase. The researchers selected the cold climate areas since the projects in these areas need to be heated during the wintertime which is not required in temperate or hot climate areas.

FRAMEWORK TO MEASURE ENVIRONMENTAL EFFECTS IN THREE DIMENSIONS: TRANSFORMATION, FLOW AND VALUE

Most researchers focus on green building rating systems from a transformational perspective. They focus on the embodied GHGs in the products (construction materials) and the transportation of the product from the source to the project. However, they neglect the processes and their associated operations effects, so they miss the impact of the wastes related to flow and value. Lean thinking guides the process of construction in a complementary way. It deals with construction as a production system that has three dimensions: transformation, flow, and value. Within those dimensions there is an opportunity to improve environmental performance. We developed a framework to measure the environmental effects of construction projects from these three dimensions (transformation, flow, and value) (Figure 1). The framework integrates the transformation, the flow, and the value for all the processes executed in the project and it considers the environmental impacts resulting from not achieving the value within the required time frame. The framework highlights the missing elements in the current state of the green building rating systems. Those missing elements relate to flow and value. Missing flow aspects are waiting, inspection, rework, construction method, and weather conditions. Missing value aspects include value delay (not achieving the value within the required time frame due to project schedule overrun), not achieving the value at all, and overdesign of parts (e.g. excessive slab thickness, steel reinforcement) and of building systems (HVAC, elevators, etc.).

We compare the effects of the flow dimension in two construction projects with contrasting management methods executed in cold climates. One of them is assumed to be managed traditionally, and the second to be managed using lean and VDC management approaches. The aim is to test the impact of location cycle time on the environment by consuming different types of fuels for heating during the winter. The two cases highlight the importance of reducing the waiting time between the different construction processes during the construction phase to improve the environmental performance of the construction process in cold climate areas.

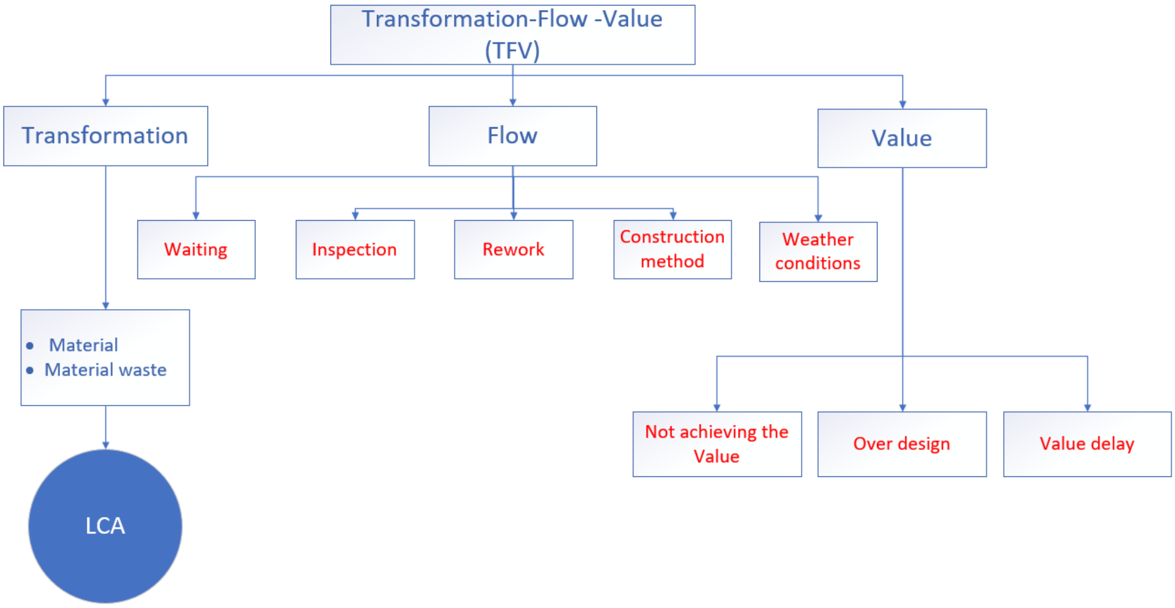

Figure 1: Framework to measure the environmental impacts based on the TFV theory. The boxes with red text represent missing elements in current assessment methods.

METHODS AND DATA

A case study research method was used to study the flow effects on the project's energy consumption. Detailed data, which include start and finish dates for each floor for two high-rise residential construction projects, were collected from the control department of a construction company in a temperate climate region but simulated in a cold climate region by calculating diesel consumed by heaters for heating the project. The two identical projects selected represent two different construction management approaches. The first project was a traditional project without any BIM or lean implementations, while the second project was managed using VDC, 5S and the last planner system (LPS).

The start and finish dates for each floor were used to draw the flow line charts for the two projects using Excel. Two hypothetical cases were evaluated: location optimization to remove the location waiting and crew optimization to remove the crew waiting. The cycle time is defined as the total time from the start of processing of a product until completion. This allows assessment of the marginal impact of implementing VDC, 5S, and LPS in reducing the cycle time. The diesel consumption for heating the construction projects was calculated based on the cycle time for the three scenarios in the hypothetical cases.

LCA following ISO (14040/ 44, 2006) was used to quantify the GHGs results from heating the construction project. Life cycle assessment (LCA) is a framework for evaluating the environmental impacts of products and materials (ISO, 2006). Many researchers used this framework to assess the environmental impacts of products within the economy, including building materials and construction projects (Junnila et al. 2006; Miller et al. 2019; Tian and Spatari 2022). The embodied GHGs were calculated for heating the construction projects in the different flow scenarios to test the flow effects from an environmental perspective.

CASE STUDY DESCRIPTION

The first author has worked in cold climate areas, and observed the amount of diesel consumed by heaters to heat the construction project. During the winter, temperatures declined to around 30 ºC below zero, which means all construction activities, equipment, and cranes must be stopped unless the construction site is heated to create safe working conditions, which required increasing the ambient indoor temperature to 5 ~ 10 ºC above zero. Heating is required before, during, and after casting concrete (to enable the chemical reactions) as well as for the different finishing activities and mechanical, electrical, and plumbing (MEP) system installations (to prevent cracking or breakage of fittings and pipes). These activities consume tremendous amounts of energy to guarantee appropriate work conditions, and the losses are very high because the heating is required for open spaces which are not enclosed or insulated, or enclosed with temporary materials.

The fuel used by heaters is diesel, which has a very high carbon footprint. The cradle to grave GHGs, which include extraction, processing, transport and distribution, and combustion, in one liter of diesel fuel is 3.31 kg CO_2e (One Click LCA, 2023). Each diesel heater consumed 18 liter/hour, and there were tens of heaters around the construction site. Some of these heaters worked 24 hours before and after casting the concrete. Hence, the space cycle time has a strong effect on the environment in cold climate areas, which is neglected within the green building rating systems, and the potential importance of optimizing construction workflow to improve environmental performance during the construction phase.

Detailed data for the start and finish dates for each activity in each location were collected from the control department of a construction company for two identical residential projects completed by the same construction company in a temperate climate zone. The data were used to build line of balance charts for the projects and calculate the space cycle times and the space waiting times.

The first project is a residential construction project consisting of 23 floors with six typical apartments on each floor with an area of 600 m^2. The activities studied are the structural system and six finishing activities: the partitions, electrical, plumbing, HVAC, plaster, and flooring. Virtual design and construction (VDC) using Revit and lean construction principles like LPS and 5S were applied in the project. VDC produced highly detailed models for the partitions, electrical, plumbing, HVAC, plaster, and flooring systems, which accounted for all interactions between these systems and optimized their arrangement. During preparation of the VDC model, the VDC manager shared the ideas with the different crews, who in turn removed the clashes between trades' systems, to plan and optimize the activities sequence. VDC played an important role in reducing the scope and frequency of changes that result from a lack of coordination between different design disciplines. Also, the VDC model helped the construction manager, and engineers in supplying the right quantities to the right location at the right time. Also, in this project, the company applied LPS including look-ahead planning and weekly work planning meetings to improve the workflow and reduce location and crew waiting.

The second project is a residential construction project, which consists of 23 floors with six apartments on each floor with an area of 600 m^2. The activities studied are the same as the first project. This project was built and managed traditionally without any lean or VDC implementations. This project was built and managed by the same company in a period before they started their BIM and lean journey. So, this project was used as a benchmark to test the marginal impact for implementing the lean and VDC practices in reducing the space cycle time and waiting time.

We assumed that diesel heaters were used for heating the construction project in each case to guarantee the appropriate temperature inside the construction project. The heating was assumed to be used mainly for the structural systems, the mechanical and electrical works, and the finishing works. While this paper presents a case study in cold climate areas, the work acknowledges that in temperate and hot climate areas, construction companies do not heat construction projects.

FINDINGS AND RESULTS

The as-performed data from the two construction projects were used to compute the floor cycle times and the associated diesel consumption for heating in cold climate areas. Two additional hypothetical scenarios were considered using simulation:

a) Process optimization, in which tasks from the original schedule were considered to be performed as soon as possible, resulting in continuous work in the locations and minimum cycle-time.
b) Operations optimization, in which the crews were assumed to have continuous work.

Table 1 lists the cycle time for each floor for the two projects with their hypothetical scenarios. The results reveal considerable differences in the cycle time between the traditional project and the lean-VDC project. The average actual cycle time was reduced from 189 days in the traditional to 115 days in the lean-VDC project, a reduction of 64%. Figures 2 and 3 present the flow line charts for the lean-VDC project and the traditional project for the three scenarios (original, location optimization, and crew optimization).

Regarding the hypothetical scenarios, the difference in the cycle time between the original state and the location optimization state for the lean-VDC project is 6 days with a percentage of 6%. However, in the traditional project, the difference is 88 days with a percentage of 87%. These results demonstrate that the location waiting in the lean-VDC project is significantly lower than that of the traditional project. This reduction is mainly due to implementing the Last Planner System (look ahead planning and the weekly work planning), which considered reducing the waiting for both the location and the crew and this shows that the general contractor succeeds to manage the subcontractors to achieve global optimization rather than local optimization.

In the lean-VDC project, the difference in the cycle time between the actual and the crew optimization is 101 days with a percentage of 88% (Figure 4). This means that if the general contractor leaves the subcontractors to manage themselves, the project duration will be extended dramatically. However, applying LPS from the phase planning to the weekly planning meeting results in balancing the work packages between the different subcontractors. In the traditional project, the difference in the cycle time between the actual and the crew optimization is 143 days, with a percentage of 75%. This implies that the subcontractors in this case managed the project from their perspective to achieve local optimization.

From a fuel consumption point of view, the amount of diesel consumed for heating the spaces was measured for the traditional and lean-VDC projects (Table 2). The amounts of diesel were calculated for each floor along its cycle time and then normalized per meter square of the finished building. The average amount of diesel consumed for heating one floor in the traditional project is 13,624 litres, whereas the lean-VDC is 8,264 litres, a reduction of 65%. In the traditional project, the average amount of diesel required for heating a floor in the ideal state (location optimization) is 7,294 litres. The difference between the actual state and the ideal state is 6,330 litres, or 87%.

Table 1: The floor cycle time (CT) in workdays for the different scenarios: original, location optimization, and crew optimization in the Lean-VDC and the traditional approaches.

Floor number	Lean and VDC management			Traditional management		
	Original	Location optimization	Crew optimization	Original	Location optimization	Crew optimization
	CT	CT	CT	CT	CT	CT
23	95	113	229	197	117	254
22	96	102	224	204	126	262
21	89	108	223	193	100	264
20	111	121	234	202	93	274
19	112	111	229	173	94	278
18	101	105	231	180	93	285
17	119	113	237	185	92	291
16	125	109	233	192	111	299
15	126	104	226	170	115	308
14	124	111	226	177	93	316
13	117	105	218	202	103	342
12	104	93	208	207	87	349
11	117	105	212	190	87	353
10	127	111	207	190	136	354
9	114	98	199	196	84	361
8	114	101	202	198	88	364
7	125	117	208	179	78	367
6	119	104	202	179	128	368
5	131	127	209	172	88	372
4	133	106	206	177	102	378
3	139	117	208	186	100	388
2	112	108	202	192	105	394
1	90	112	203	211	110	415
Average	**115**	**109**	**216**	**189**	**101**	**332**

In the lean-VDC project, the average amount of diesel required for heating a floor in the ideal state is 7,829 litres, and in the actual state is 8,264 litres. The difference is 435 litres, or 6%. This shows that the actual state in the lean-VDC project is not too far from the ideal state. The total GHGs in the Lean-VDC project is 629-ton CO_2e, while in the traditional project it is 1,037 tons CO_{2e}. The difference between the traditional and the Lean-VDC project is 408 tons CO_{2e}, a reduction of 65%.

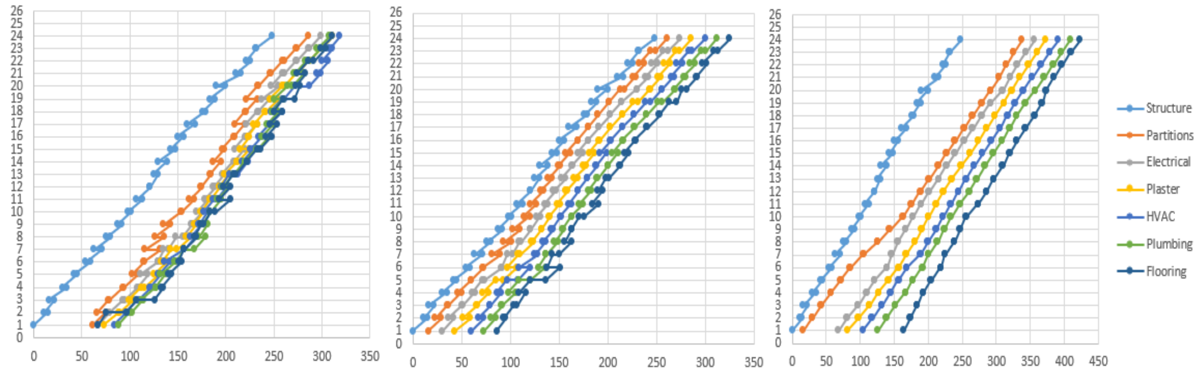

Figure 2: Flow line charts for the lean-VDC project with three scenarios: original, location optimization, and crew optimization (from left to right).

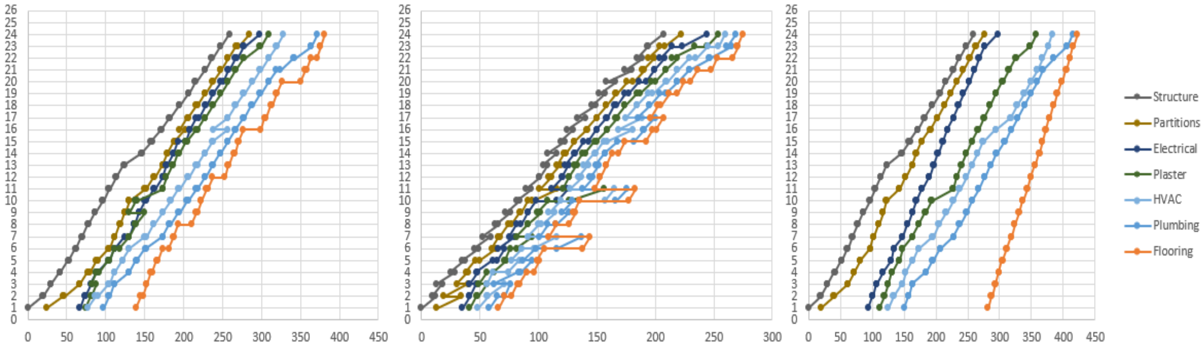

Figure 3: Flow line charts for the traditional project with three scenarios: original, location optimization, and crew optimization (from left to right).

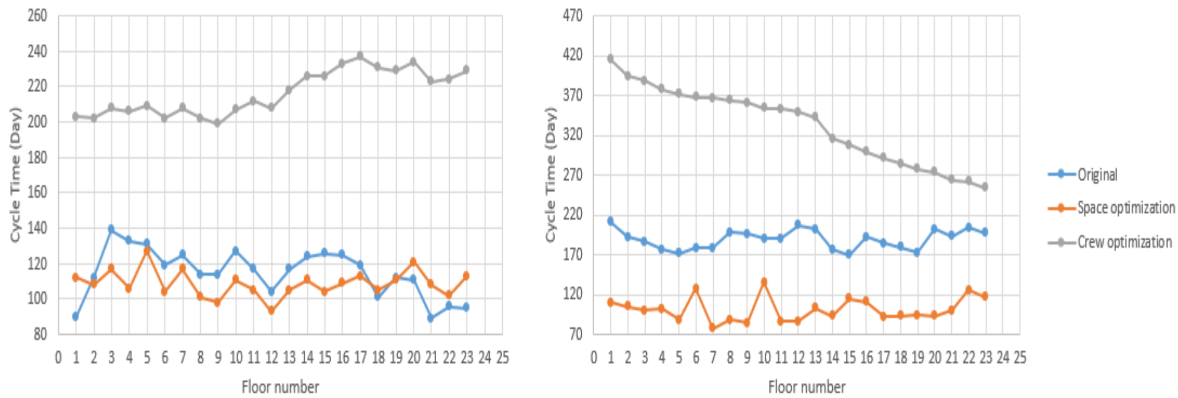

Figure 4: Cycle time for the different floors in the different scenarios for the lean-VDC (left) and traditional (right) projects.

Table 2: The amount of diesel for the different scenarios: original, location optimization, and crew optimization, in the Lean-VDC management and the traditional management approaches

Floor number	Lean and VDC management			Traditional management		
	Original	Location optimization	Crew optimization	Original	Location optimization	Crew optimization
	Diesel (litre)	Diesel (litre)	Diesel (litre)	Diesel (litre)	Diesel (litre)	Diesel (litre)
23	6,840	8,136	16,488	14,184	8,424	18,288
22	6,912	7,344	16,128	14,688	9,072	18,864
21	6,408	7,776	16,056	13,896	7,200	19,008
20	7,992	8,712	16,848	14,544	6,696	19,728
19	8,064	7,992	16,488	12,456	6,768	20,016
18	7,272	7,560	16,632	12,960	6,696	20,520
17	8,568	8,136	17,064	13,320	6,624	20,952
16	9,000	7,848	16,776	13,824	7,992	21,528
15	9,072	7,488	16,272	12,240	8,280	22,176
14	8,928	7,992	16,272	12,744	6,696	22,752
13	8,424	7,560	15,696	14,544	7,416	24,624
12	7,488	6,696	14,976	14,904	6,264	25,128
11	8,424	7,560	15,264	13,680	6,264	25,416
10	9,144	7,992	14,904	13,680	9,792	25,488
9	8,208	7,056	14,328	14,112	6,048	25,992
8	8,208	7,272	14,544	14,256	6,336	26,208
7	9,000	8,424	14,976	12,888	5,616	26,424
6	8,568	7,488	14,544	12,888	9,216	26,496
5	9,432	9,144	15,048	12,384	6,336	26,784
4	9,576	7,632	14,832	12,744	7,344	27,216
3	10,008	8,424	14,976	13,392	7,200	27,936
2	8,064	7,776	14,544	13,824	7,560	28,368
1	6,480	8,064	14,616	15,192	7,920	29,880
Average	**8,264**	**7,829**	**15,577**	**13,624**	**7,294**	**23,904**

CONCLUSIONS

The two hypothetical construction projects analysed herein show that lean principles like VDC and LPS play an important role in reducing the project duration and the location cycle times, which is a crucial issue in cold climate areas. The average original project cycle time was reduced from 189 days in the traditionally managed to 115 days in the lean-VDC managed project, a reduction of 64%. Also, the difference between the average cycle time in the original scenario and the location optimization is six days which means that the general contractor succeeds to manage the subcontractors to achieve global optimization rather than local optimization. However, in the traditionally managed project, the difference in the average cycle time between the original scenario and the location optimization scenarios was 88 days, which means that the sub-contractors achieved local optimization rather than global optimization, resulting in extending the project cycle time.

From an environmental point of view, the amount of diesel consumed in the lean-VDC managed project is 8,264 litres, while in the traditional managed project it is 13,624 litres, a variance of 5,359 litres (65%). The amount of energy used for heating the construction project, which has a significant impact on the environment, could be reduced due to implementation of lean and VDC management approaches.

We conclude that lean practices like LPS and VDC play an important role in improving the workflow and reducing the project cycle time by achieving global optimization rather than local optimization. This contributes to dual benefits for the sub-contractors and the general contractors (win-win relation). Also, the results show the importance of reducing the project cycle time in cold climate areas. The total GHGs reduced from 1,037 tons CO_{2e} to 629 tons CO_{2e}, a reduction of 65%.

These results underscore the importance of reducing the project cycle time from an environmental perspective in cold climate areas. However, this is not the case in temperate or hot climate areas since there is no need to heat the project. Other environmental factors should be investigated in these areas, such as workers' transportation from and to the construction project, or the camp energy consumption in cases where workers live at the construction site.

This research focuses on the effect of heating construction projects during the construction phase. It focuses on cold climate areas since it is needed in these areas, and there is no need for heating in temperate and hot areas. Other issues like workers traveling from and to the construction site, energy sources used for operating equipment, and machines like cranes, elevators, etc, should be considered in the different climate areas. Although these issues are not quantified in this paper, the researchers suspect that they will have considerable impacts on the environment and will be shared between cold, temperate, and hot climate areas. Considering all these emissions will amplify the results. Further research should include these emission sources to visualize the process effect from an environmental perspective.

RESEARCH LIMITATIONS

This paper explored the effect of heating construction projects in cold climate areas by using hypothetical case studies from temperate climate areas and assessing them in cold climate areas. Recently, the researchers have begun collecting data from a project in a country classified as a cold climate area, and in the future, more representative results from the cold climate areas will be published.

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LEAN CO-ACTING WITH CIRCULARITY? AN INVESTIGATION IN PRODUCT-SERVICE SYSTEMS IN RENTAL HOUSING

David Parker[1], Tuuli. E. Jylhä[2], Gerard A. van Bortel[3], and Daan F. J. Schraven[4]

ABSTRACT

Circularity is positioned as an alternative model to achieve sustainable prosperity. Lean construction highlights not only building delivery with less but also contributing to sustainable development. However, lean is criticized for reducing waste only within organizational boundaries while neglecting the impact of waste beyond the boundaries. On the contrary, circularity originates to reduce waste in the system and is currently seeking approaches to implement waste reduction in circular production. To speed up the transition to sustainable resource consumption, the co-act between lean and circular construction seems evident. This research studies resource consumption in product-service systems (PSSs), which are acknowledged to reduce resource consumption. This research first assesses the ability of PSSs to slow and close the loops. After this, the research discusses the complementarities of circularity and lean to co-act toward the same goal. The multiple case studies demonstrate that PSSs have the potential to slow and close the loops. However, PSSs are not inherently circular, but each PSS needs to be designed to be circular system-by-system. Furthermore, the theoretical discussion encourages lean to co-act with circularity. The PSSs provide a system view to lean: to reduce current and future waste and to avoid value losses in multiple life cycles.

KEYWORDS

Circularity, servitization, product-service system, building components.

INTRODUCTION

In recent years, circularity has been introduced as means to sustainability in many scholars, including the built environment and construction studies (e.g., Benachi et al. 2021, Munaro et al., 2020; Ghaffar et al., 2020). For example, Chen et al. (2022) stated that circularity in construction could be "a new model to retain the value of resources and to prevent the use of virgin materials and waste outputs, not only by recycling and reusing of materials but also primary by reducing the need for resources". Furthermore, circularity in general is proposed to be the transformative model for sustainable prosperity (Azevedo et al., 2017; Lacy et al., 2020). Similarly, lean construction literature highlights not only building delivery with fewer resources but lean delivering sustainable prosperity (Huovila & Koskela, 1998; Novak, 2012a; Novak 2012b). At the same time, product-service systems (PSSs) are recognized as an alternative

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model to reduce resource consumption while ensuring economic growth (Lacy et al., 2014). In PSSs, commonly known as Product-as-a-Service (PaaS), the customer pays for access to the product and its functionality, which in traditional models are acquired through ownership. When the PSS provider stays the owner of the product, the PSSs provider is incentivized to extend the lifespan and usage of the product and its materials, and to reduce costs (Halme et al., 2004). However, it remains unclear to what extent PSSs are circular (Fernandes et al., 2020; Van der Laan & Aurisicchio, 2020).

PSSs are not widely studied in lean construction literature although servitization in general has started to receive more attention in the construction sector due to the paradigm shift "from delivering a product to satisfy the user needs" (Liu et al. 2021). Servitization in the construction sector is mainly implemented either in the operation phase (such as in maintenance, energy management, or in security), or in production servitization, where "construction activities are conceptualized as construction services" (such as material supply services or computing services) (Liu et al., 2021). To summarize, servitization adds value to the existing products, while PSSs utilize services to contribute to dematerialization.

Although waste reduction is one of the key concepts in lean, lean is criticized for focusing on "the immediate usage of the resource within a specific process" (Nadeem et al., 2019) and missing the system level, i.e., the environmental and economic impact beyond the organizational boundaries (Schmitt et al., 2021). Circularity does take the system perspective when optimizing resource usage from one life cycle to another while (Nadeem et al., 2019). On the other hand, current circularity research is seeking approaches to reduce resource consumption on the process level. Schmitt et al. (2021) stated that lean could "increase the efficiency of all circular flows, thus greasing the wheels of circular economy". For example, Kurdve and Bellgram (2021) studied how lean can operationalize circularity on the shopfloor level. The general complementarities between circularity and lean encourage further investigation of the co-act between circularity and lean construction.

To summarize, both lean and circularity have a common interest to reduce resource consumption. PSSs are argued to reduce resource consumption, but it remains unclear to what extent PSSs are circular. This leads to a twofold aim. First, to assess the ability of PSSs to slow and close the loops according to the circularity principles and second, to discuss the complementarities of circularity and lean to co-act towards the same goal in PSSs. A multiple case study approach was selected to analyze the ability of PSSs to slow and close loops in Dutch rental housing. The Netherlands is experiencing an urgent housing crisis. It is estimated that 900,000 homes need to be built before 2030 to arrange for homes for the increasing population and address the current housing shortage (Ministerie van Binnenlandse Zaken en Koninkrijksrelatie, 2019). At the same time, the Netherlands has set an ambitious goal to improve the energy efficiency of the current housing stock and to develop a circular economy by 2050, and to reduce the consumption of raw materials by 50% by 2030 (Government of the Netherlands, 2016). This also applies to the Dutch housing sector. The ambition to expand and improve the housing stock in the Netherlands can lead to a huge increase in resource consumption but also pose an opportunity for innovation, such as PSSs, and incorporating circular economic principles in residential buildings.

The remaining paper is structured into four parts. First, PPSs are presented including the four models: input-, availability-, usage- and performance-based models. After this, the method section presents the multiple case study method and the selected PSSs. The results outline the ability of PSS to slow and close the loops according to the circularity principles case-by-case and across cases. Finally, the discussion focuses on interpreting the results and theorizing complementarities between lean construction and circularity in PSSs.

PRODUCT-SERVICE SYSTEMS

Historically, the target of the companies has been to sell their products to their customers. In the 1980's and 1990's, many companies searched for solutions to create and capture more value in the competitive market. Within this search, some companies decided to start selling products and services together to better serve their customers. This was discussed as 'servitization of businesses' (Vandermerwe & Rada, 1988) and it is currently gaining increased attention in the race towards circularity due to its ability to reduce resource consumption.

In the traditional economic models, producers are typically motivated to reduce cost via mass production: by providing standard quality without the incentive of providing products with long lifespans (Mont, 2002). Another typical quality in mass-production is that the maintenance responsibility of the product is transferred to the buyer at the moment of the purchase. This all leads to resource-intensive production and consumption. From PSSs perspective, the circular incentives aim to reduce resource consumption through two approaches. In the first approach, the customer owns the product, and the producer offers maintenance and a take-back program for the customer. This approach does not guarantee that the product will be returned to the producer (Van Ostaeyen et al., 2013). In the second approach, the ownership of the product remains for the producer and the customer has access to use the service. This type of ownerless consumption ensures that the product is returned to the producer (Van Ostaeyen et al., 2013). When the producer sees the returned product as an asset and the material is recycled in the next production line, the "take-make-dispose" logic is broken without risking economic growth.

There are four principles to evaluate the circularity ability of PSSs as established by Bocken et al. (2016). The first two principles represent the product's capability to slow and close loops. Product slowing the loops refers to prolonging the use period of the product (Bocken et al., 2016). In the PSSs context, this typically refers to the product's capability to receive preventive maintenance. Product closing the loops refers to reusing the materials through recycling (Bocken et al., 2016). The authors (2016) list three design strategies to close the loops: design for a technological cycle, design for a biological cycle, and design for dis- and reassembly. These strategies enable easy use of the product components or material in the next loop. The last two principles refer to the ability of business models to slow and close loops. When a business model is slowing the loop, it enables a long product life span and reuse of products (Bocken, et al. 2016). For example, the business model allows that the product is used to its maximum, or that the residual value of the product, as Bocken et al. 2016 call it, is (fully) exploited in the same or in another PSS. Finally, the circular business model closes loops, when being able to capture *"the value from what is considered in a linear business approach, as by-products"* (Bocken et al., 2016). In PSSs, this means that the product or its components, and material are recycled.

Four types of PSS systems can be distinguished (Van Ostaeyen et al., 2013): input-, availability-, usage- and performance-based models each characterized by different fee structures and levels of servitization (Figure 1). The servitization level is the lowest in input-based and the highest in performance-based models. Next, these four PSS models are briefly introduced in a housing context.

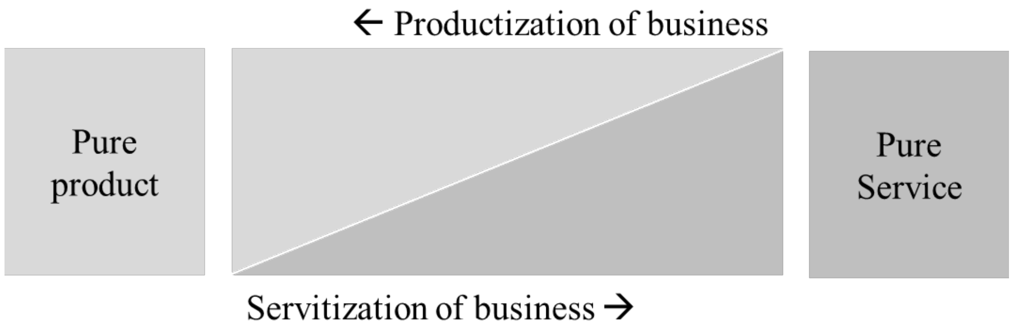

Figure 1: Servitization and Productization (in Parker (2021), based on Vandermerwe & Rada (1988), Tukker (2004) and Leoni (2015).

INPUT-BASED MODEL

In the input-based model, the housing provider owns the product and pays service fees to the PSS provider for the services that are needed to operate the product. The services may comprise, for example, product maintenance, supply of consumables, product's pay-back program, and consultancy services for the user to ensure that the product is used efficiently and effectively (Tukker, 2004). A typical example from the housing sector is a heating boiler that the housing provider purchases, including an agreement for maintenance and inspection and a take-back program at the end of the product's lifespan.

AVAILABILITY-BASED MODEL

In the availability-based model, the PSS provider owns the product, and the housing provider leases it. The fixed recurring fee paid by the housing provider includes the product's availability regardless of how much it is used. In addition, the fee needs to cover the maintenance and repairs that keep the product in operation (Tukker, 2004). Furthermore, for the duration of the model, the availability is only pertained to the one that pays, meaning that the product or is usage is not shared. A typical example in the housing sector is a kitchen that is owned and maintained by the PSS provider and leased by the housing provider.

USAGE-BASED MODEL

In the usage-based model, the PSS provider owns the product, and the housing provider leases it. Compared to the previous model, the major variation is that the housing provider pays for the usage of the product, not for the product's availability (Van Ostaeyen et al., 2013). A typical example in the housing sector is the lease of an elevator: the housing provider pays a lease based on the annual distance traveled by the elevator and the PSS provider retains the ownership and keeps the product in operation.

PERFORMANCE-BASED MODEL

In this model, the housing provider pays a leasing fee to the PSS provider only when a desired performance is attained. In this model, the PSS provider, as the owner of the product, adjusts and maintains the product to attain the required performance level (Tukker, 2004). A typical example of this type of model is companies that do not only provide heating and cooling equipment, but instead provide a defined indoor climate (temperature, humidity, and indoor air quality) (Tukker, 2004). Performance-based housing products were not yet identified within the housing market; thus, this model was excluded from the empirical research.

RESEARCH METHODS

MULTIPLE CASE STUDY APPROACH

PSSs in buildings could target products or services at multiple building layers. A distinction for building layers was discussed by Brand (1994): structure, skin, services, space plan, stuff, and site. Different building layers have different duration of service lives and offer different functions that a building user could enjoy and pay for. For example, renting furniture in an empty home would target the building layer 'stuff', but could be changed based on users' taste in style. On the other hand, the choice of stone or wood for structural and insulation, could not be changed by every new tenant of a buildings' whims. Therefore, the implications for choosing a workable PSS may vary with targeting these different building layers.

To analyze a variety of products from multiple building layers and a variety of PSS models (including input, availability, and usage models), our research follows a multiple-case study approach. Multiple case study design allows replication (Yin, 2013). In this research, this means that the circularity of PSSs is studied among variety of products and business models to make analytical conclusions about the capability of these systems to slow and close the loops. This replication ensures that similar types of findings are found if they exist. Table 1 summarizes the case study selection criteria.

Table 1: Case study selection.

		Cases						
		A	B	C	D	E	F	G
Represents a variety of PSS models:	Input	x						
	Availability		x	x	x			
	Usage					x	x	x
Possible to include both perspectives: housing provider and PSS provider		x	x	x	x	x		

Seven cases were selected to cover the three PSS models: input-, availability- and usage-based models, based on a variety of building layers and PSS types. The size and market position of the housing provider and PSS provider vary per case. In five cases (cases A-E), two interviews were done per case: an interview with the representative from the housing provider and from the PSS provider. In the two cases (cases F-G), the representative from the housing provider was unavailable and the interviews were limited to the representative from the PSS provider. All 12 interviews were conducted in spring 2021 and they were recorded and transcribed for the analysis.

INTRODUCTION TO THE CASES

In this section, all the cases are briefly introduced. In case A, a PSS of two existing elevators in a residential building of 78 apartments is studied. The housing provider owns the elevators and has a 5-year service contract with an extension option with the PSS provider. The housing portfolio of the housing provider includes 10.000+ rental homes, and the housing provider has used PSS before in their portfolio.

In case B, PSS kitchens are studied in a project where an office building was transformed into housing. 15 of the PSS kitchens are based on a lease-to-own service contract with a pay-back program. The housing provider has paid an installation fee to the PSS provider and is also responsible for the recurring service payments. One kitchen is owned by the PSS provider (as a pilot) and the housing provider pays a service fee for it. The housing provider is a small, young organization in the social housing sector managing a 5-year-old, small portfolio of rental homes at the time the case study was conducted. This was their first PSS purchase. The PSS provider is also a beginner in the field and at that moment has installed 10 PSS kitchens.

Case C is also a transformation case from office to housing. In this transformation project, an availability-based model is used for 130 windows. The windows are owned by the PSS provider and the housing provider only pays the recurring service payments – no installation fees or down payments are part of the deal. At the time, the housing provider had a portfolio of 10+ housing buildings and had operated for 12 years. This was their first PSS project. The PSS provider had a long business experience (30+ years), but this was also their first PSS contact.

In case D, the study object is the PSS of a battery storage system in a 50-apartment housing building. The PSS provider owns the battery storage system. The housing provider has paid an installation fee and is responsible for the recurring service payments (no down payments were included). The housing provider has a large portfolio of social rental homes (16.000+), and the PSS provider has sold more than 100 PSS batteries.

Case E is another elevator case study but with a different PSS model: 14 elevators are installed in a new construction project including a total of 485 homes, of which 200 are rental homes owned by the housing provider. In this case, the PSS provider is the owner of the elevators, and the housing provider only pays recurring service payments based on the usage of the elevators – there are no down payments or installation fees for the housing provider. The PSS provider has sold the product (i.e., elevator) for more than 65 years and since 2017 with the PSS model. Their PSS portfolio includes 200+ elevators.

Case F includes the PSS of a heat pump in a housing building including 27 homes. The PSS provider owns the heat pump, and the housing provider only pays recurring service payments based on usage – there are no down payments or installation fees for the housing provider. The housing provider is an association that owns and rents the residential units for long term. At the moment the case study was conducted, the PSS provider has sold this product for 2+ years and installed 3 PSS heat pumps.

In case G, solar panels are installed on the existing residential buildings. The PSS provider owns the solar panels, and the housing provider only pays recurring service payments based on the usage – there were no down payments or installation fees for the housing provider. The housing provider is a long-term owner in social housing and the PSS provider has at that moment sold their PSS panels for 9+ years.

RESULTS

The results are first presented case by case including table 2, which summarizes each case. After this, the results of the cross-case analysis are discussed.

SINGLE CASE STUDY ANALYSIS

In case A, the analysis identifies that circularity is supported through preventive maintenance of the elevator. The input model encourages preventive maintenance, and this maintenance extended the lifespan of the elevator. The interviewee from the housing provider stated: "*They* [=the PSS provider] *have the diagnostics, and they can support us in making the right decisions. And they can also know the equipment that we're replacing and parts we're adding to make the useful life longer*." In other words, the product can receive preventive maintenance and the PSS model offers that maintenance. This slows down the resource loops.

In case B, the analysis finds many circular aspects. The kitchen design itself allows easy repair and maintenance that is also provided through the availability-based PSS model. This means, for example, that the fronts are changed after 5 years if the kitchen is used intensively. In other words, the product and the availability model slow down the resource loops. In addition, the disassembly design of the kitchen and the PSS model allowed the product to be looped into another destination by extending the product value. The PSS provider in case B stated: "*For* *the appliances, indeed, it's all about companies, eventually taking back their product and using it in the highest value possible at the stage. That's either directly using it again, refurbishment, remanufacturing, and you go down the R-ladder in the end, recycle. And that is something that we put in the contract.*" This indicates that the product and the PSS model contribute to slowing and closing the loops.

In case C, the analysis also identifies many of the circular aspects. First, the PSS provider was responsible for keeping the quality of windows as high as possible. The representative of the PSS provider said: "*We have a long-term performance contract with them to keep the quality as high as possible so that we can enlarge the lifespan of the materials*." This means that the product itself and the related service slow down the loops. In addition, both the housing provider and the PSS provider highlighted that the product and/or materials are looped again after the disassembly. For example, the representative of the housing provider stated that "*You push the manufacturer to think about their product, how is this going to be disassembled, how it is going to be brought back in the loop again*" and the representative from the PSS provider stated that *"...100% must be recycled and reused. [...] We set up the new brand, in the DNA is already embedded that we just reuse it till the end*.". This means minimized extraction of natural resources: the business model and the product are closing the loops through looping the products and/or materials and through a principle that only looped products and/or materials are allowed to be used.

In case D, it was not found that the product itself (i.e., the battery) is contributing to slowing or closing the loops, but that the business model is. The availability-based PSS allowed that the PSS provider exploits the residual value of the batteries: the remaining lifespan of the replaced batteries was utilized in smaller systems, where they were still suitable for use. This utilization extended the lifespan of these batteries, i.e., slows down the loops.

In case E, the analysis identifies many circular aspects to slow down and close the loops. As in case A, in this case the lifespan of the elevator is extended through advanced maintenance. In other words, the PSS extends the lifespan of the elevator (slowing the loop). The business models are also aiming to slow down the loops by utilizing the residual value of the materials, including the creation of reverse logistics. The estimation was that "*if these materials are not available anymore, they will become more expensive*", as the representative of the PSS provider in case D stated it. In addition, the product itself and the usage-based PSS, in which the PSS provider is the owner of the elevator, contribute to closing the material loops. It was stated by the representative of the PSS provider that approximately 90% of the elevator parts are recycled and the remaining 10%, that is electronic parts, are not. This contributes to closing the loops.

In case F, the analysis does not identify any circular aspect of the product or the related business model. The business model does provide preventive maintenance, but this maintenance is not expected to extend the lifespan of the heat pump. The material of the heat pump is also not reused or recycled. The PSS provider stated: *"It is very difficult to take out the materials. We've asked now, the heating suppliers, to make a system which can be [a] modular system where you can take out some blocks in 15 years and put in back another, which they do, of course, but they don't do it with the vision of how to reuse [it]."*

In case G, the analysis finds only one aspect that supports circularity: preventive maintenance expands the lifespan of solar panels. The solar panels are designed for preventive maintenance but not for disassembly. This means that the residual value is not utilized and circular input is not generated. The representative from the PSS provider stated: "*Either the solar panels are very good, and everything is normal, so we keep on doing it [...]. Or we reinvest exactly after 20 years, put new panels on, and everything is continued [...]*.".

Table 1: Summary of the case studies.

	Cases						
	A	B	C	D	E	F	G
Product: slowing loop	x	x	x		x		x
Product: closing loops		x	x		x		
Business model: slowing loops	x	x	x	x	x		x
Business model: closing loops		x	x		x		

CROSS-CASE STUDY ANALYSIS

In slowing down the loops, preventive maintenance seems to play a key role in the PSS cases. The business model provides preventive maintenance and extends the lifespan of the product. In addition, due to the circular product design, the product can receive predictive maintenance. Together these aspects slow down the loops. This was found in five cases out of the seven (in cases A, B, C, E, and G). Case D did not follow this logic in slowing down the loops. In case D, the loop was slowed down through the business model that kept the ownership of the product with the PSS provider, who could, after replacement, use the remaining lifespan of the product in another system with another client. This means that the lifespan of the product is used to its maximum, i.e., the business model (not the product) slows the loop.

In closing the loops, the disassembly or deconstruction ability of the product was instrumental in the easy use of the product and its materials in the next loop. In addition, the business model was designed to catch the product from one loop and to deliver it to another through recycling (cases B, C, and E). Contrary to expectations that the usage-based model closes the loops effectively, as proposed for example by Ostaeyen (2013), cases F and G did not contribute to closing the loops: the product, nor the usage-based PSS, were designed for reusing the product or its materials.

To conclude, PSSs have a high potential to be circular when the product and the service in the system are designed for circularity. However, not all PSS are inherently circular meaning that the use of PSSs does not automatically lead to circularity.

DISCUSSION

Within the highlighted role of circularity in sustainable development, PSSs are commonly accepted business models to reduce resource consumption. Based on the existing literature, it was expected that the utilized circularity principles are increased when moving in the PSS axis of input-availability-usage. However, this was not the case in this research, where the 7 PSS cases were conducted and analyzed. The results imply that the PSSs are not inherently circular, but each PSS needs to be designed to be circular system-by-system. Similar results can be found in the literature (e.g., Blüher et al., 2020; Tukker and Tischnener, 2006). The results do not imply that PSSs should not be used to contribute to achieving circularity but that the PSSs need careful design at all the stages of design.

This paper claims that PSSs provide an example for circularity and lean construction to co-act towards the same goals – to reduce resource consumption and to deliver sustainable prosperity. Benachio et al. (2021) studied "the interactions between lean construction principles and circular economy (CE) practices". We see these interactions as natural interfaces for circularity and lean construction to co-act and supplement each other. In their paper, Benachio et al. (2021) recognize the CE practice that is studied in this paper: ownerless consumption, where the manufacturer stays the owner of the material. Benachio et al. (2021) refer specifically to the moment after the end-of-life of the first building meaning that the manufacturer takes responsibility for and makes an opportunity at the first looping moment. In PSSs, the system can take on this responsibility, when, as the cases A-E and G illustrate, the product and/or the business model are designed for that. For example, in case C the manufacturer carried on the responsibility of the first loop of the windows as was also done in case D with the battery although the product itself did not support circularity.

After studying circularity in PSSs, the discussion is moved to postulate key complementarities between circularity and lean in PSSs. In general, lean and circularly deal with two key concepts – value and waste – but have major differences in embracing these concepts. Complementarities can be explained via these concepts.

In lean, value is defined by the customer (e.g., Womack and Jones, 1996; Ballard et al., 2001; Salvatierra-Garrido et al., 2008) and the flow is made at the pull of the customer (e.g., Womack et al., 1990; Howell and Ballard, 1998). In circular terms, material is seen as a source of value, and the value of resources is used to the maximum in the life cycle of the material (Nadeem et al., 2019; Bocken et al., 2016; Schmitt et al., 2021). Nadeem et al. (2019) interpret this as a limitation and argue that this kind of “highest utility of resources all the time” accelerates the resource depletion. In closed loops, the circular philosophy highlights upcycling meaning that in recycling and reusing the value of the material should be retained or improved (Bocken et al., 2016). To conclude, the concept of value in circularity does not include the customer’s perspective and the concept of value in lean does not include the maximum use of the material value.

In PSSs, the two value concepts complement each other. According to Romero and Rossi (2017), PSSs deliver value-in-use. From a lean perspective, the PSS extends the concept of value from one life cycle to another, for example by utilizing the residual value of the product in another system (such as in cases D and E). In terms of lean, the use of the residual value would avoid future value losses. From a circularity perspective, PSSs ensure that only the needed resources are consumed. PSS makes sure that the resource is consumed at the time it is needed (i.e., at the pull).

Similarly, waste is seen differently. In lean, waste refers to the use of more than needed and unwanted output (Bølviken et al., 2014). Furthermore, the non-value-adding activities are removed through continuous improvement (in Japanese kaizen) (Imai, 1997). Waste in circularity has another meaning. In a closed-loop system, waste from one life cycle is used as a resource (i.e., source of value) in another life cycle. Wasted resources are transformed into new forms of value, as outlined in Bocken et al. (2016). By slowing the loops, the prolonged use postpones the end of the resource’s life. When products and parts are designed for dis- and reassembly, they are easily looped in other cycles (Bocken et al., 2016).

In PSSs, the waste concepts complement each other. The concept of waste from lean can improve the operational efficiency of PSSs. Romeno and Rossi (2017) have studied circular lean PSSs and they claim that lean can eliminate “waste in the manufacturing activities and services operations that affect the PSS efficiency”. Unfortunately, circular systems do not widely acknowledge that resources are wasted in the circular processes themselves. Korhonen et al. (2018) stated that “all CE-type initiatives, projects and activities generate environmental impacts and consume resources”. In the PSS cases, the production of circular elevators, windows, or kitchens consumes resources, as does the preventive maintenance of these products. Lean focuses on throughput optimization on the shopfloor (Schmitt et al., 2021). Therefore, the concept of waste lean can complement circularity by operationalizing waste reduction on the shop floor and increasing the operational efficiency of the circular production system itself (Schmitt et al., 2021).

The circularity of PSSs complements the concept of waste in lean. PSSs provide a system approach to lean, not only to reduce resource consumption in the current process but from one life cycle to another. This means that future waste is reduced, when the product is designed for dis- and reassembly and thus easily reused, recycled, or remanufactured. To be circular, lean needs to build its reserve production practices.

CONCLUSIONS

Within the highlighted role of circularity in sustainable development, PSSs are commonly accepted business models to reduce resource consumption. In lean construction, PSSs as such are not highlighted. Therefore, this paper first assessed the ability of PSSs to slow and close the loops; and after this, discussed the complementarities of circularity and lean to co-act towards the same goal. A multiple case study approach was followed.

The case studies imply that PSSs are not inherently circular, but each PSS needs to be designed to be circular system-by-system. This does not imply that PSSs should not be used to contribute to achieving circularity, but that PSSs need careful design at all the stages of design. Furthermore, the theoretical discussion encourages lean to co-act with circularity in PSSs. PSSs provide a system view to lean: not only to reduce resource consumption and deliver value in the current processes but also from one life cycle to another. This would mean that future waste is reduced and that the value losses are avoided when the value of resources is fully exploited. For circularity, lean offers an approach to reduce resource consumption in the circular processes themselves by operationalizing waste reduction on the shop floor. Furthermore, the integration of the customer's perspective into the concept of value ensures that circular products are used at the pull of the customer. It is advisable to investigate these complementarities not only systematically further within a PSS but also between PSSs.

The paper has its limitations. First, the research on PSS types in the building context is quite novel empirically, rendering only a handful of cases that can be easily studied. The case selection is limited to the input-, availability- and usage-based PSS models since no performance-based models were available for this study. Secondly, this research is limited to qualitative assessment of resource consumption based on interviews. In future studies, quantitative data are needed to assess the effectiveness of PSSs in reducing resource consumption. Thirdly, as many organizations are still new to the PSS workings, the results may themselves have an impact on how practitioners are still learning and working with these business models. Fourthly, the notion that the design of the model has an influence on its ability to achieve circularity, implies that more design choices need to be explicit for this relation to be studied more targeted. Lastly, the lean analysis was not part of the original data analysis in the cases. This limited the lean discussion on the theoretical level urging to continue studying the topic with real cases in the future.

Recommendations resulting from the study include a few notable directions. First, as more applications in practices are piloted and upscaled, research studies like these need to keep pace with the collective learning, if we are to generalize the true nature of PSS on circularity. Second, more emphasis in future studies needs to be performed on the specific design choices for PSS applications, the object, and the level of achieved or intended circularity. Lastly, due to circularity and lean acting alone towards the same goal, it would be interesting to further explore the co-acting possibilities between lean and circularity in the construction sector. Alone the journey towards delivering sustainable prosperity might be faster, together we might go further.

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CHOOSING BY ADVANTAGES (CBA) TO SELECT THE BEST LOCATION FOR A SOLAR PHOTOVOLTAIC PLANT IN THE PRE-FEASIBILITY STAGE

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ABSTRACT

The energy transition from fossil fuels to pollution-free and sustainable energy has been a common goal for all countries worldwide. In line with this transition, the Peruvian industry and many others worldwide seek to develop new renewable energy projects. Solar photovoltaic energy is the preferred option due to the significant potential in its territory. This research aims to show the application of the CBA methodology in selecting the best location for a solar Photovoltaic (PV) plant to develop a pre-feasibility study whose area of interest are the Peruvian Andes. The analysis was based on identifying the advantages of each factor considered in evaluating the best sites for the location of a solar PV plant. The results showed that the CBA methodology is very important when performing pre-feasibility studies for solar PV plants, where costs do not make substantial differences between alternatives. This research will be a valuable tool for the community of professionals in developing renewable energy when performing pre-feasibility studies in which there needs to be more information on the area of interest. The aim is to define the location with the best solar photovoltaic potential.

KEYWORDS

Choosing By Advantages, Solar PV Plant, ubication, Lean Construction, Sustainability, decision-making.

INTRODUCTION

Energy consumption by the world's population has increased exponentially in recent years, so the search for new energy sources, preferably renewable and non-polluting, has become necessary. Solar energy has been approaching as a solid response to the problem and has gained ground in the main first-world countries, spreading over the years to developing countries (García de Fonseca et al., 2019). However, constructing facilities for energy generation using

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solar panels, which capture sunlight and convert it into energy, has required rigor and demand for the correct energy supply to society. Determining the best construction location for the solar plant is one of the critical points when seeking to generate energy (Aly, 2017) since it influences the technology of solar panels, the amount of energy produced, ease of construction, and economic costs, among others.

That is why different researchers have applied mathematical methods to select the location of a solar plant. Wang et al. (2018) proposed using a Multi-criteria Decision-making model (MDCM) that combined three methodologies, including Data Envelopment Analysis (DEA), Fuzzy Analytical Hierarchy Process (FAHP), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). On the other hand, Sánchez-Lozano (2013) proposed combining the Geographic Information System (GIS) and MDCM methods such as AHP and TOPSIS. The aforementioned mathematical methodologies are the ones that are mainly used in research on the selection of the location of solar plants.

Although these applied mathematical methods help us decide, they do not adapt to different cases or extract the project context (Martínez et al., 2016). One method adapted to the projects and the context is Choosing By Advantages (CBA), a decision-making system developed by Suhr (1999), whose importance lies in the advantage of the factors rather than the factors themselves. CBA has applications in different topics, including those related to sustainability.

Goh et al. (2022) apply CBA for the selection of the location of a solar plant in Southern California, USA, during the feasibility stage. This application of CBA is focused on a reality that has different characteristics, first at the level of development phases (the information available at a feasibility stage is very different from that of a pre-feasibility stage), and then at the country level, considering the deficiencies in Peruvian regulations regarding the promotion of renewable energies. (Gamio et al., 2017). The study of the quantification and tabulation of meteorological data from stations between 1975 and 1990 (Tamayo, 2011) determined that compared to other countries, Peru has solar energy availability in almost all of its territory, being large and uniform throughout the year (SENAHMI, 2003).

Therefore, the following research aims to implement CBA for the selection of the location of a solar plant in Peru in the pre-feasibility stage. To this end, a literature review on the decision-making methods in solar plants is carried out, followed by the implementation of CBA. Then the results are discussed to evaluate whether the factors change by geographical location and project development stage.

BACKGROUND

In this section, the authors will initially discuss Choosing by Advantages (CBA) due to its relevance to understanding the difficulties in determining a construction site for a photovoltaic solar plant.

DECISION MAKING IN SOLAR PLANTS

The appropriate location of a solar PV plant is the most critical decision in project design and subsequent construction (He-Yau & You-Jyun, 2017). Thus, some authors have developed different decision-making methods to solve this problem. One example is El-Azab & Amin (2015), who proposed an algorithm to optimize the selection of locations to build a solar plant in North Africa and the Middle East and applied it to a case study in Egypt. The algorithm defined the average global solar radiation for each day, calculated the transmission losses, and calculated the average energy generated in a year. Finally, the net transmitted energy of all alternatives was compared to choose the option that generates the most energy in a year.

Thongpun et al. (2017) used the DEA method to select the location of a solar plant in Thailand based on the efficiencies of plant sites in 77 provinces in Thailand. Factors affecting the efficiency of solar panel systems, energy output power, and solar plant area selection were considered: resource availability, economic impact, environmental concern, social concern, and accessibility. Once the study was completed, efficiency percentages were obtained for a linear and non-linear DEA model.

Rezaei et al. (2017) investigated seven regions in the Iranian province of Fars to assess the best location for constructing a wind-solar hybrid power plant. Wind and solar potential were considered the most critical factors. This information was obtained using the Weibull distribution function and the Angstrom-Prescott equation in the Meteorological Organisation of Iran database from 2006 to 2015. The method consisted of using fuzzy TOPSIS for data analysis and ranking, then MCDM methods (AHP, DEA) were used to verify the results obtained.

Lee, Kang, and Liou (2017) propose a multi-criteria decision-making model to choose the best construction site for a photovoltaic solar plant in Taiwan. The model consists of using interpretive structural modeling (ISM) to determine the interrelationship between criteria and sub-criteria, then using fuzzy analytic network process (FANP) to obtain the weights of the sub-criteria, and finally, multi-criteria optimization and compromise solution (VIKOR in Serbian) to rank the photovoltaic solar plant locations. After the application, it was obtained that the most important criteria were costs and physical environment. At the same time, the most critical sub-criteria were land utilization, land cost, repair and maintenance cost, and soil quality.

Rediske et al. (2020) proposed a model for the location of photovoltaic power plants in the central region of Rio Grande do Sul - Brazil. The model consists first of an area analysis with the gvSIG software, using the AHP method to give weight to each factor, and finally using TOPSIS for the order of alternatives. An area of 1823.35 km2 was studied, determining that 19.91% was excellent for the location of a solar plant. They considered the most critical factors of the environmental type, location, climate, geomorphological, Substation Distance, and Solar Irradiation.

CHOOSING BY ADVANTAGES & SUSTAINABILITY

CBA is a multi-criteria decision-making system based on the importance of "advantages" between alternatives (Suhr, 1999), which includes principles and definitions, where models, methods, tools, and techniques are also concentrated. The CBA system includes methods for virtually all decisions, from the very simple to the very complex. Among all these methods, Arroyo (2015) indicates that the most used is the Tabular CBA Method. In the construction industry, there are many applications where this method can be used; mainly, it has been applied in different sustainable decisions, showing many benefits, for example:

Arroyo et al. (2013) applied this method to improve decision-making in selecting ceiling tiles, showing benefits such as identifying relevant sustainability factors, providing documentation for rational decision-making, and identifying relevant advantages to make transparent, transparent, and conflict-free exchanges between options. Also, Arroyo et al. (2015), in a commercial interior design project, chose a sustainability alternative for roof tile materials; the study contributed to knowledge by integrating stakeholder perspectives considering sustainability factors, identifying sustainability factors according to context, and how to discriminate IofAs, among others.

Arroyo et al. (2016) compared CBA and Weighting Rating and Calculating (WRC) in groups of professionals to make decisions involving sustainability factors in architecture, engineering, and the construction industry.

Torres-Machi et al. (2019) evaluated the sustainability of pavement management decisions. AHP and CBA are used in a case study comparing pavement maintenance technologies using cold-in-place recycling and traditional solutions based on mill and overlay.

Perez and Arroyo (2019) used CBA and Design Structure Matrix (DSM) to redesign the waste collection program. CBA was used for three complex decisions and supplemented with

DSM to decrease negative iterations by finding the proper order of decisions. By applying CBA, sustainability solutions are achieved, and by applying DSM, it was possible to solve the problem of being able to consider decisions.

Milion et al. (2021) used CBA to classify the impact of defects in residential buildings and improve sustainable managerial decisions where risk can affect the quality of projects from the customer's perspective.

Finally, Goh et al. (2022) apply CBA for the selection of the location of a solar plant in Southern California, USA, during the feasibility stage. Through an exhaustive literature review, Goh et al. (2022) identified the different factors in their decision-making. The factors that obtained a higher score for decision-making are in the following order: solar irradiation potential, policies, and payback period.

RESEARCH METHODOLOGY

CASE STUDY

The case study is selected due to the importance of solar PV energy in the energy development strategy (Goh et al., 2022). The case study consists of a project for a Potential Study (typical of a pre-feasibility stage) for the conception and development of a solar PV plant in the Andean region of Peru. Therefore, the two most relevant aspects for the project owner were: the location of the asset (close to important cities in the Andean region of Peru) and the capacity and energy yield of the solar PV plant. However, due to the experience and knowledge of the professionals involved in the project (technical staff), additional criteria were established for developing an asset of this type. Therefore, the area of interest had to be studied for different location options.

Thus, four alternatives with appropriate characteristics and conditions for a solar PV project are proposed, from which the best one has to be chosen. For this reason, it is necessary to consider a methodology that enables one to decide based mainly on value, which will be discussed in more detail in the following sections.

CHOOSING BY ADVANTAGES

For the CBA application to determine an optimal construction site for a photovoltaic solar plant, the decision involved the participation of an electrical specialist, a geographic information specialist, a hydrological specialist, a geotechnical specialist, and a renewable energy specialist. Due to the fundamental role of the participation of the professionals involved in the project in defining the context of the decision (Martinez et al., 2016), the CBA Tabular Method allows for capturing the perspectives of decision-makers with different opinions. The steps involved in applying the CBA Tabular Method are detailed in the seven steps indicated in Figure 1:

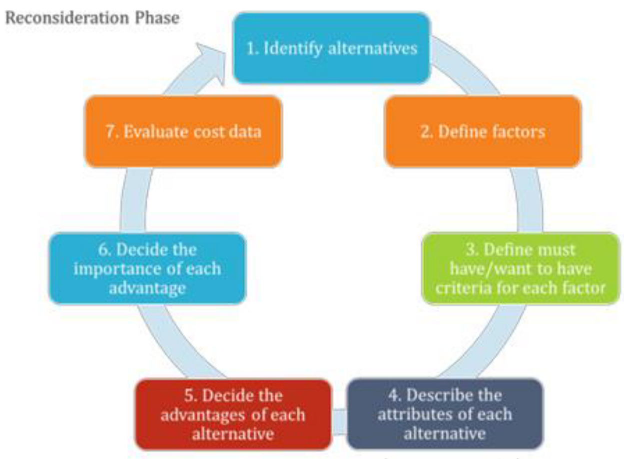

Figure 1: CBA Tabular Method steps (Arroyo, 2022)

The application of the steps of the CBA Tabular Method in the case study will be explained below:

Step 01: Identify the alternatives

A preliminary analysis is made in an area near major cities in the Andean region of Peru. Next, a suitable construction site is sought for the location of a photovoltaic solar plant. In this step, the project team identified four zones as alternatives (Table 1).

Table 1: Alternatives of Case Study

Alternatives	Description of the alternative
Alternative 1	Location A in the central Peruvian Andes, of approximately 888 hectares.
Alternative 2	Location B in the central Peruvian Andes, of approximately 1375 hectares.
Alternative 3	Location C in the central Peruvian Andes, of approximately 694 hectares..
Alternative 4	Location D in the central Peruvian Andes, of approximately 975 hectares.

Step 02: Define the factors

The project team needs to identify factors that support discerning the best alternative among those listed. Following the review of relevant literature and consulting with industry experts, six essential factors for site selection are suggested as follows in Table 2:

Table 2: Factors of Case Study

Factor	Unit of measurement	Description of the factor
The slope of the land	The measure of slope [%]	It is essential to know the slope of the land when the owner wants to build a solar PV plant on the site because the lower the slope, the shading effect will be. The slope also affects how it will be built (whether it will require additional work) or whether the land is appropriate for construction.
Distance to the connection point	The measure of distance in Kilometer [km]	The distance to the connection point (electrical substation or transmission line) where the energy will be directed must be considered when designing the solar PV plant. The longer the distance, the higher the transmission losses.
Availability of area for future expansions	The measure of surface area in Hectare [Ha]	The project owner has expressed his long-term interest in further developing photovoltaic generation in the country. Thus, this project would be a first step in its strategy and seek to expand the solar PV plant in the coming years.
Condition of access routes	-	The condition of the main access roads to the alternatives is important to make the most efficient choice. Poor road conditions can cause problems during the construction of the solar PV plant.
Power generation	Amount of energy generated (kWh) per installed capacity (kWp) (Specific	Solar power generation is a crucial factor, as this influences the capacity and energy yield of the future solar PV plant.

	energy production) [kWh/kWp]	
Presence of protected ecosystems	-	The presence of protected or endangered flora or fauna within or near the solar PV plant in a country as biodiverse as Peru implies elaborating a detailed environmental management plan, a series of inconveniences with land use permits, or even the impossibility of using the site for a photovoltaic generation.

Step 03: Define the criteria for each factor

The criteria to select the best alternative among the four available are based on the degree of impact on the project's viability. These have been based mainly on the Preliminary Selection Criteria, the analysis criteria of the field visit, and the estimated generation in the Preliminary Evaluation of Photovoltaic Energy Production (shown in Table 3).

Step 04: Describe the attributes of each alternative

The information collected from the four alternatives is used to obtain the attributes according to the factors and their criteria mentioned in the previous steps. The least preferred attribute is underlined and will serve as a point of comparison to describe the advantages (shown in Table 3).

Step 05: Decide the advantages of each alternative

Criteria are applied to identify advantages. In this case, the team first identified the least preferred attribute, highlighted it, and then used it as a basis for the comparison with the other attributes in each factor. Then, differences are defined as the advantages of the alternatives. The most significant advantage for each factor is shown in red and italics in Table 3.

Step 06: Decide the importance of each advantage

This part of the process is collaborative, and decisions are reached through discussion within the project team and the technical staff. A factor listed the most preferred advantages, and they are given an order of priority to define which are the most relevant when choosing an alternative.

Subsequently, a ranking is generated with weighting where the IoA (Importance of Advantage) is defined as the supreme advantage (a most important advantage when the decision is made) with a value of 100. Then, the IoAs of the other most preferred advantages is defined, always having as reference the value of the supreme advantage. Finally, with the IoAs for the most preferred advantages already defined, the IoAs for the other advantages were calculated proportionally (shown in Table 3).

Table 3: Evaluation using CBA Tabular Method

Factor (Criterion)		Alternative 1		Alternative 2		Alternative 3		Alternative 4	
Land Slope	Att.:	**3% - 5%**		**5%-10%**		**5%-10%**		**3%-5%**	
(The less, the better it is)	Adv.:	It has less slope	Imp 40		Imp		Imp	It has less slope	Imp 40
Distance to connection point	Att.:	35 Km		**11 Km**		29 Km		**47 Km**	
(The closer, the better it is)	Adv.:	12 Km closer	Imp 20	36 Km closer	Imp 60	18 Km closer	Imp 30		Imp
Area availability	Att.:	888 Ha		**1375 Ha**		**694 Ha**		975 Ha	
(The more available, the better)	Adv.:	194 additional Ha	Imp 3	661 additional Ha	Imp 10		Imp	281 additional Ha	Imp 4
Condition of access roads	Att.:	Medium		**Bad**		Medium		**Good**	
(The better condition, the better it is)	Adv.:	Better condition	Imp 20		Imp	Better condition	Imp 20	Much better condition	Imp 30
Energy generation	Att.:	**2121.7 kWh/kWp**		2174.9 kWh/kWp		2252.1 kWh/kWp		**2313.7 kWh/kWp**	
(The more it generates, the better it is)	Adv.:		Imp	53.2 kWh/kWp more	Imp 28	130.4 kWh/kWp more	Imp 54	192 kWh/kWp more	Imp 100
Presence of protected ecosystems	Att.:	**Not found**		**Yes**		**Not found**		**Not found**	
(The less presence, the better it is)	Adv.:	Less presence	Imp 50		Imp	Less presence	Imp 50	Less presence	Imp 50
Total IoA		133		98		154		224	

Step 07: Evaluate cost data

In this step, the project team did not evaluate costs because this research is related to the pre-feasibility stage of a project to construct a photovoltaic solar plant. At this project stage, costs do not generate differences between alternatives, so selecting the best alternative was based only on value.

DISCUSSION

In order to select the 4 study alternatives, an exhaustive search had to be carried out in the area of interest so that, based on the established factors and criteria, four sites with attractive attributes could be determined for further study.

Thus, the application of the CBA Tabular Method for the selection of the best alternative for the location of the solar PV plant has proved to be convenient, as it has taken into account factors typical of a pre-feasibility study that can lead the way for the large-scale development of solar PV projects and, why not, also of renewable energy projects in general in Peru.

In this way, it was possible to define the advantages of each factor considered, which is classified by the technical staff who adopted the methodology with great enthusiasm. In Peru, value is only sometimes prioritized in engineering and construction projects. Therefore, some benefits gained were training staff in CBA and identifying the value of each alternative in an engineering project. Meanwhile, barriers to implementing the CBA method were the initial unwillingness of top management to leave conventional methods behind and the time for staff training in CBA.

During this discussion, it was determined that energy generation was a preponderant factor in the project's conception. It will be the source of income that will make the project viable throughout its useful life and is closely linked to the other factors. The other factors were also considered relevant in the analysis, but taking into account that, for example, there are projects by the Peruvian State for the improvement and expansion of the National Interconnected Electricity System and the National Road Network; these will eventually have a lower preponderance than energy generation.

Compared to Goh et al. (2022), who conducted similar research where they applied CBA for the location of solar panels in Southern California in San Bernardino and Riverside counties, the research has shared certain factors.On the one hand, while in the present investigation, the factor of "power generation" has been taken into account, Goh et al. (2022) considered the "solar irradiation potential" factor, both alluding to the fact that it is important to consider the amount of energy that would be produced due to the position of the solar plant that would allow it to capture the most significant amount of sunlight.

Another couple of factors that are also similar between the present investigation and the investigation in California are, respectively, "Condition of access routes" and "Distance to roads/substations." Both factors refer to the fact that it would be more appropriate to select a place with easy access to reduce as much as possible the costs of transporting materials or equipment and to facilitate the construction of the plant. Regardless of the context of the work, the factors mentioned above will likely be considered when deciding the location of the solar plant due to its high impact on value generation. However, other factors may or may not become part of the analysis, depending on the context of the decision that comes to be considered when applying the CBA (Martinez et al., 2016).

Goh et al. (2022) mentioned that sixteen factors were obtained to apply the CBA, which were obtained due to the assistance of experts and important institutions worldwide. For that reason, special consideration was not taken to the context of the place. On the other hand, the present investigation considered only six factors that are focused on the context of the project. For this reason, there is a big difference between the factors used in both investigations. For example, we have the factor "availability of area for future expansions," which is essential in selecting this research because the project owner has shown great interest in expanding the photovoltaic solar plant. Another example would be the factor "presence of protected ecosystems," which has a high preponderance in the study area due to the high biodiversity in the flora and fauna of Peru. Likewise, the main factor was power generation, which has also been considered by similar investigations that applied other MCDM methods, such as Rediske et al. (2020), Rezaei et al. (2017), Sánchez-Lozano (2013), among others.The factors that are most often repeated in this type of research are "solar irradiation," "distance to roads," and "distance to substations." In addition, in some studies, the "slope" and "distance to power lines" are considered, as in the present investigation, and others, the "agrological capacity" is considered instead.

However, the main difference between Goh et al. (2022) and the present paper is the information required for the analysis. While Goh et al. (2022) propose an analysis with 16 criteria, in which data from a feasibility study are framed, where the technical characteristics of the location are known, in this paper, we intend to establish the analysis based on identifying the potential of different locations within an area of interest, considering that the information that may be at hand (such as geology, connection conditions, among others) is minimal or non-existent. Basic design criteria will be considered for this selection.

CONCLUSIONS

The application of the CBA Tabular Method enabled selection of the best location for a solar PV plant in the pre-feasibility stage, considering the Andean region of Peru as the area of interest. As part of this analysis, it was determined that Alternative 4 is the best located for the rest, standing out mainly for its energy generation and its low slope. Other factors in its favor are the good condition of its accesses and the absence of protected ecosystems within or near the alternative. As factors in which it does not have an absolute advantage over the rest, we can mention a smaller area available for expansion (compared to Alternative 2) and the distance to the connection point. These factors should be re-evaluated later (during feasibility) to determine whether they can improve their contribution to the value of the project.

This study aims to contribute to developing renewable energy projects at a preliminary stage (pre-feasibility), mainly in Peru, which has one of the world's most considerable solar PV potentials (Gamio, 2017). It also seeks to promote the use and study of the CBA decision-making system in various industry and engineering sectors, applying it in this case to a project closely linked to sustainability, climate change, and energy transition.

The results obtained indicate that the application of the CBA Tabular Method helps to select the best alternative for the location of a solar PV plant based on the value it provides, considering that in the development of pre-feasibility studies, the costs are referential and do not mark essential differences between the alternatives.

Likewise, the authors suggest implementing other lean principles in solar plants: process management in the evaluation of photovoltaic solar assets (value stream mapping), implementation of the last planner system in the construction of photovoltaic solar plants, application of lean project delivery system in the development of photovoltaic solar projects and others. Specifically, as the next steps for extending this research, further research on selecting equipment (technology) in solar photovoltaic plants and applying Choosing By Advantages decision-making system should be performed.

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ANALYSING FILM PLASTIC WASTE IN RESIDENTIAL CONSTRUCTION PROJECT

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ABSTRACT

Sustainability and lean construction are closely interrelated topics to consider. However, sustainability issues in construction projects are rarely discussed in International Group for Lean Construction (IGLC) community. The major aim of this research is to analyze the film plastic waste in residential construction project. For the analysis, three cases were selected, where the amount and quality of film plastic waste were investigated from the beginning of project to the end. According to the results, 1009–1710 kg of film plastic waste was separately collected (about 0.5–1.0% of total waste). In addition, the generated pattern of film plastics was approx. 0.34 kg/m2 and each apartment generated approx. 26.20 kg. The most film plastic is generated in the interior phase of the work stage, which includes tasks such as partition work, furniture installation and home appliance installation. Furthermore, based on the results of this research, we have developed a preliminary web modelling tool: kalvomuovi.fi, which could be adopted for estimating the amount of film plastic waste in a residential construction project. Future research could further develop the web model tool for other type of construction projects, such as, schools, hospitals, and shopping centers. Also, future research is necessary to develop better recycling technology of film plastic waste.

KEYWORDS

Green construction, film plastic waste, modeling platform- kalvomuovi.fi, lean construction

INTRODUCTION

Green construction and plastic use are currently an issue of major concern that has sought significant attention of media, policymakers, environmental activists, as well as academic practitioners (Mikkonen et al., 2020; Häkkinen et al., 2019; Ramboll, 2020; Yle, 2021). The main concern with the dramatic increase in the use of plastic has been its significant and adverse effect on human health, as well its potential contribution to climate change and environmental degradation and toxicity.

According to Material Economic (2018), the plastic use is increasing by 10 million metric tonnes per year, and it is estimated to reach 800 million metric tonnes per year by 2050. The plastic industry is intricately linked to the global economy. It is considered the seventh most value-adding industry in Europe, which consists of about 60000 companies and provides about 1.5 million jobs with a value of about 350 billion euros (Häkkinen et al., 2019). Muoviteollisuus (2021) estimates that in Finland the plastic industry consists of almost 600 companies and employs over 10,000 people. It is estimated that, on average, Finnish residents produce about 15 kilos of plastic waste per year (Yle, 2020). In response to this problem, Kosonen and Varis

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(2019) presented a plastic roadmap for Finland, which suggests several actions for reducing, reusing, recycling, and replacing plastic.

Due to various advantageous properties of plastic, such as lightweight, flexibility and dielectric properties, it has been used in different applications. Häkkinen et al., (2019) mentioned that about 45 % of plastic is used for packaging, 19% is used for construction, 12 % in consumer products, 7% in transportation, 4 % electronics and 12 % is used for other applications. They further indicated that a very small portion (about 10%) of plastic is recycled while the rest is discarded which ultimately end up in landfill.

The use of plastic in building and construction improves the physical health of a building by ensuring good thermal moisture and gas insulation performance (Schiavoni et al., 2016). In construction, plastic is used in building products and materials, for instance, flooring, windows, insulation products, and kitchen. Plastic is present in construction products, as a building material, and film plastic is also used for packaging construction materials.

In fact, it has been argued that film plastic is used significantly in construction activities, for instance, for construction product packaging, site workers' food packaging, and also during different work stages (Ramboll, 2020). A few studies have analysed the plastic packaging waste in construction (E.g. Pericot et al, 2014; Pericot and Merino, 2011; Selke and Culter, 2016). They mention that primarily plastic packaging waste were the films. However, their results include the sheets and rigid forms of packaging plastics (e.g. crates). Also, the research on packaging plastic waste excludes the films produced on site, for instance, films used in site protection and site works and activities. Film plastic normally ends up in the landfill due to difficulties in the recycling centres. For all those reasons, research on film plastic waste is explicitly necessary. To the best of our knowledge, till date there has been no research on the use of film plastic in construction. Specifically, this research aims at answering the following research questions:

- How to collect film plastic waste from a construction site?
- How much film plastic waste is created in construction projects (mostly residential)?

THEORETICAL BACKGROUND

PLASTIC IN CONSTRUCTION

According to Plastic Europe (2020) about 4000 million metric tonnes of plastic was produced from 1950 to 2019. This amount mainly includes, polypropylene (PP), polyvinylchloride (PVC), polyethylene (PE) polyethylene terephthalate (PET), polyurethane (PU), polystyrene (PS), and polyester (PES) (Häkkinen et al., 2019; Napier, 2016). Table 1 presents the plastic type composition, physical properties, and possible application in construction.

Table 1: Plastic types and possible application in construction (Awoyera and Adesina, 2020

Plastic types	Physical properties	Application in construction
HDPE	Rigid	Table, chairs, plastic lumber
LDPE	Flexible	Bricks and blocks
PP	Hard and flexible	Aggregates in asphalt mixture
PS	Hard and brittle	Insulation material
PET	Hard and flexible	Fibres in cementitious composites
PC	Hard and rigid	Aggregates in cementitious composites

Even though various types of plastics are used in the construction sector; PVC, Polyethylene-high density (PE-HD), Polyethene low density (PE-LD), PP and EPS (Expanded Polysterene) are mostly common. Table 2 presents the types of plastic generated in the building and construction sector in the EU in 2018 (Plastic Europe, 2019).

Table 2: Building and construction plastic waste generation in the EU in 2018 (in kt)

Plastic types	Total waste generation	Recovery	Disposal/landfill
PE-LD	90	70	20
PE-HD	225	164	61
PP	130	95	35
PS	30	21	9
EPS	140	95	45
PVC	910	683	228
Other	235	172	63
Total	1760	1300	461

Plastic quantity used in construction depends on building types, products, and work stages. For instance, Monahan and Powell (2011) estimated the use of plastic to be 7.4 kg/m2 in a model-house study. Ruuska and Häkkinen (2015) presented 12-21 kg/m2 in a block of flats. Furthermore, Jeffrey (2011) argued that approximately 1% of total construction demolition to be of plastic. Similarly, Häkkinen et al., (2019) evaluated the quantity and types of plastic in concrete and wooden residential buildings and day care centres. Their findings showed plastic quantity to range from 6 to 28 kg per gross m2.

FILM PLASTIC IN CONSTRUCTION

The demand for film plastic is increasing worldwide. For instance, in 2015, the film plastic demand rose in Asia by 40% and in Western Europe and North America the demand was equally significant (18%) (Stastista, 2015). The increasing demand for film plastic is associated with its diverse applications. Essentially, such applications can be divided into two groups: packaging and non-packaging. In packaging, film plastic is used to protect the product itself, which is called primary packaging, and also film plastic is for safe transportation of the product as a secondary packaging (Hellström and Sagir, 2007; Horodytska et al., 2018). Non-packaging use includes, for example, films from construction, agriculture, trash bags, etc. In general, all plastic could be formed into film plastic, however, based on the polymer application, films from the PE-HD, PE-LD ja PE-LLD (polyethylene linear low-density) is mainly used in construction (Headley Pratt Consulting, 1996; Polymerdatabase, 2021).

Some studies have analyzed the packaging waste in construction. They generally include cardboard, woods, and plastic (Pericot et al., 2014; Pericot and Merino, 2011; Selke and Culter, 2016). Perico and Merino (2011) presented the the packaging waste generated in three construction site cases: 1) 100 social housing projects, 2) 118 dwellings and 3) 112 housing construction projects (table 3).

Table 3: Packaging waste in construction projects in Spain

	Cardboard		Muovi		Wood	
Cases	Weight (kg)	Volume (m3)	Weight (kg)	Volume (m3)	Weight (kg)	Volume (m3)

I (100 blocks)	2887,36	67,31	1691,71	34,73	74832,85	958,58
II(118 blocks)	4039,33	88,25	2320,35	46,25	104457,24	1225,47
III (112 blocks)	4823,45	71,15	2236,54	42,59	99823,66	1167,94
Total= 330 (blocks)	11750,1	226,71	6248,6	123,57	279113,75	3351,99

In our research, the primary focus is on analyzing the presence of film plastic in construction projects. So, while analysing previous literature on packaging waste, our emphasis is on packaging plastic.

Based on the calculation presented by Pericot and Merino (2011) the average plastic packaging waste per middle sized building (~8 floor) is about 19 kg (table 3). They further mentioned that majority of plastic packaging waste was film and sheet plastic, which were used to wrap the pallets. And, one-way slab products were the highest producer of packaging waste in construction projects.

Pericot and Merino (2011) further suggest waste management strategies for reducing plastic packaging waste in construction. They include, for example, segregation at origin by waste specific container at site, wrapping the product until it is going to be used and immediately store packaging waste once the product has been opened. According to them, this would help to maintain the product in better conditions as well as prevent it from potential packaging damages. In addition, the compactors could be used to reduce the plastic volume, and waste management training could be provided to construction staff.

Pericot et al., (2014) further studied the packaging waste of midsized ten housing blocks constructed with the Mediterranean conventional procedure. This includes, for example, deep foundations with concrete piles, one-way slabs, flat roofs, brick facades insulated with polyurethane foam and so on. Table 4 presents the average packaging waste quantities presented in their study.

Table 4: Packaging waste in different construction stages

	Cardboard		**Plastic**		**Wood**	
Construction stages	**Weight (kg/m2)**	**Volume (l/m2)**	**Weight (kg/m2)**	**Volume (l/m2)**	**Weight (kg/m2)**	**Volume (l/m2)**
Site remediation	0	0	0	0	0,01	0,01
Foundations	0,01	0,01	0	0	0	0
Structures	0,01	0,02	0,12	0,19	0,33	0,3
Envelopes	0,02	0,03	0,06	0,1	0,6	2,21
Partitions	0,01	0,02	0,12	0,19	0,64	0,59
Building services	0,88	1,18	0,01	0,02	0,13	0,12
Thermal and moisture protection			0,07	0,12		
Roofs	0,02	0,03	0,04	0,07	0,05	0,05
Finishes	0,25	0,34	0,1	0,17	0,15	0,13
Signaling equipment	0,05	0,07				
Exteriors and swimming pool	0,01	0,01	0	0	0,02	0,02
Total	1,26	1,71	0,52	0,86	1,93	3,43

According to Pericot et al., (2014) study plastic packaging waste mainly produced in the partitions (~28%), structures (~20%) and finishes works (~20%). In line with the previous research (e.g. Pericot and Merino,2011; Jang et al., 2020) they also mention that the high portion of plastic packaging waste generated from the palletizing and primarily they include film and plastic sheet.

Even though the research works mentioned above have evaluated the packaging waste in construction, their primary focus was not on the film plastic waste in construction. They mention that the majority of packaging waste was films and plastic sheets. Hanny (2002) explains that a significant portion of the packaging plastic waste included the rigid forms, especially in secondary packaging, e.g. crates and shipping pallets. Selke and Culture (2016) distinguished different packaging plastics as: Plastics with thickness of 0.003 in or less are considered film, and materials with thickness of 0.010 in or greater are considered sheet. Furthermore, studies on packaging plastic that evaluate films produced in the site such as film used for site protection, poly bags and site workers' food packaging, are missing.

FILM PLASTIC COLLECTION METHOD

Different countries have different strategies for waste collection. For instance, in the United States, two types of collection methods are used: 1. single- stream: all the waste (e.g. paper, glass, plastics and metal) are collected in the same bin, and 2. dual-stream: the waste is collected separately, such as, plastic, paper, glass and metal (Cimpan et al., 2015). Even though the dual stream process collects plastic separately, film plastic is rarely separated (Horodytska et al., 2018).

In the EU, some of the member states have adopted film plastic waste collection strategies. However, even in such countries, film plastic is still collected in the mixed plastic bin. Table 5 presents EU countries that have adopted the film plastic collection strategies.

Table 5: Film plastic collection schemes in European countries (Cimpan et al., 2015; Seyring et al., 2015; Horodytska et al., 2018)

Film collection schemes	EU countries
Co-mingled flexible and rigid plastic collection	Austria, Netherlands
Collected with mixed plastics	Germany, Slovenia, Hungary, Sweden, Spain, Portugal
Some collection with mixed plastics	France
Rigid and film plastics are collected separately	Italy
Plastic (PE) films collected separately	United Kingdom
Collected with mixed recyclables	Ireland

To evaluate the packaging plastic waste from construction site, Pericot and Merino (2011) used a tool called "SMARTAudit" where waste was quantified and categorized by source, type, number, cause, and cost. In this process, well-trained observers evaluated the volume of waste from the mixed waste container at construction site. However, they recommend placing separate plastic waste containers on construction sites for proper waste management.

Overall, the collection of film plastic waste from a construction site is not an easy task. The site needs to be equipped with different collection bins, which is not always viable. Collection may face several challenges such as busy environment of the site, lack of space, attitude of people towards waste sorting, etc. (Ministry of Environment, 2020). Even though the collection of film plastic seems to be time-consuming and extra work, it has been argued that construction projects would still benefit from avoided waste collection fees (Ramboll, 2020).

METHOD

Case study is appropriate research for in-depth investigation and multi-faceted understanding of a complex topic (Yin, 2018). Multiple sources of evidence are used in this research approach. Thus, this research is conducted based on the multiple case study approach.

For analysis, three building construction projects were selected for the in-depth investigation. They are presented in table 6. All the cases have implemented some techniques of lean. For example, all projects have adopted prefabricated products. They have adopted waste (material and process) minimization techniques, e.g., Choosing-by-advantages (CBA) in design and construction phase. The cases were selected to ensure that the amount of film plastic could be collected from the beginning of the project to the end.

Table 6: Case information and amount of film plastics

	Case 1	**Case 2**	**Case 3**
Gross area (m2)	3863 m2	5617 m2	3460 m2
Number of apartments	54	76	38
Number of floors	7	9	8
Collected film plastic waste	1596 kg (0,96 % of all waste)	1710 kg (0,53 % of all waste)	1005 kg
Film plastic waste / m2	0,41 kg /m2	0,30 kg /m2	0,29 kg /m2
Film plastic waste/ apartment	29,6 kg	22,5 kg	26,4 kg

For collecting the data, we agreed with our case projects that they would collect film plastic separately. For this, all site workers were instructed to collect the film plastic separately. To ensure that the film plastic measurement was accurate, a separate film plastic container with instructions was placed on every floor. Film plastic waste was collected in the dedicated container and measured.

According to Poon et al (2001) building construction workers are often reluctant to conduct on-site waste sorting which is considered to be time consuming and labor intensive. To address this issue, our case projects also instructed their cleaners to place film plastic waste into the right container. In addition, the project researchers also visited the site often to analyze the amount of film plastic in other containers and at the same time observed the quality of film plastic in different work stages. The amount of film plastic was obtained from the waste collector. The amount was further corrected with the amount thrown into the wrong container, even though it was almost negligible.

RESULTS AND ANALYSIS

RESULTS FROM TASK LEVEL ANALYSIS

Firstly, the amount of the films waste produced in each activity listed on the schedule was analyzed separately for our cases. The activities that required several products to be installed naturally generated bigger portion of the film's plastic. Table 7 presents the major task-level activities that generates the greatest amount of film plastic.

Table 7: task-level activities that generates the highest amount of film plastic

SN	Task -level activities	Case 1 (kg)	Case 2 (kg)	Case 3 (kg)
1	Furniture installation	187,42	112,64	65,14
2	Ceilings of apartments	121,51	93,87	43,43
3	Partition work	93,31	93,87	52,73
4	Wooden windows and balcony doors	92,22	156,45	67,21
5	Laminate	88,91	93,87	20,68
6	Wall tiling	84,57	112,64	68,24
7	Roof	75,01	35,20	38,77
8	Leveling works	67,52	112,64	43,43
9	Final cleaning	65,25	156,45	51,70
10	Bathroom installations	59,27	56,32	55,83
11	Aco wall installation	55,74	117,34	15,51
12	other	605,00	568,20	485,75
	Total	**1596,00**	**1710,00**	**1009,19**

After analyzing the amount of film plastic waste in each activities of our cases, we then organized tasks in the following five construction stages, which allow the comparison of the results obtained in every project:

1. Foundation: Foundation wall, Foundation pillars, beams
2. Frame and roof: Frame of building, roof work
3. Interior work: Partitions, furniture installation, home appliance installation
4. MEP installation: Mechanical, electrical and plumbing work
5. Finishes and closures: Operational tests, official inspections

TOTAL AMOUNT OF FILM PLASTIC WASTE

In all cases, the portion of the film plastic waste was about 0.5-1% of total waste. The total amount of film plastic ranged from 1005 kg to 1710 kg. According to the U.S. Environmental Protection Agency (2016)'s volume-to-weight conversion, 1 kg of film plastic will occupy 0.05 m^3 of container space if the films are stored without heavy compression. This conversion is used to evaluate the volume of film plastic in our cases. Table 8 presents the number of films produced in each site per works stages and their volume:

Table 8: Total amount of film plastic in each case

SN	Tasks	Case 1 (kg)	Case 1 (m3)	Case 2 (kg)	Case 2 (m3)	Case 3 (kg)	Case 3 (m3)
1	Foundations	45,39	2,27	31,29	1,56	27,92	1,40
2	Frame and roof	156,11	7,81	132,98	6,65	183,01	9,15
3	Interior work	819,20	40,96	934,01	46,70	548,51	27,43
4	MEP installation	573,05	28,65	596,08	29,80	244,39	12,22
5	Finishes and closures	2,26	0,11	15,65	0,78	5,17	0,26
	Total	**1596,00**	**79,80**	**1710,00**	**85,50**	**1009,00**	**50,45**

As table 8 demonstrates, film plastic was mostly produced in the interior Workstage. It's mainly due to the activities such as partition work, furniture installation and home appliances installation—where most of the product required installation and their packaging plastic constituted the high amount. On the other hand, a minimal amount of film plastic waste was generated in finishes and closures. This is apparently because this stage involved mostly administrative tasks where no product installation is required.

Following the trend that interior activities produce most of the film waste, we have considered that the total area of the building and the number of apartments is the major factors for film plastic waste production. It is also visible in table 12 that case 1 produces the greatest amount of film waste, mainly due to the higher gross area and number of apartments. The total amount of film plastic generated in respect to gross area is presented in table 9.

Table 9: Total amount of film plastic per 100m2

NRO	Tasks	Case 1 (Kg/100m2)	Case 2 (kg/100m2)	Case 3 (kg/100m2)	Average (KG/100m2)
1	Foundations	1,17	0,56	0,81	0,85
2	Frame and roof	4,04	2,37	5,29	3,90
3	Interior work	21,21	16,63	15,85	17,90
4	MEP installation	14,83	10,61	7,06	10,84
5	Finishes and closures	0,06	0,28	0,15	0,16
	Total	**41,32**	**30,44**	**29,16**	**33,64**

While comparing the three case results, case 1 has produced the higher amount of film plastic waste. However, case 2 has the higher gross area and number of apartments. Citing the discussion with case 2 project personnel, some amount of film plastic was thrown into the other containers by mistake by the site workers. And, from our site visit observation and discussion with the project personnel, film plastic was collected as accurately as possible in case 1. Table 10 further presents the films plastic waste per apartment. Analyzing the result of the three cases, each apartment of residential building will produce about 26.20 kg of film plastic waste.

Table 10: Amount of film plastic waste per apartment

SN	Tasks	case 1 (Kg)	Case 2 (KG)	Case 3 (kg)	Average (KG)
1	Foundations	0,84	0,41	0,73	0,66
2	Frame and roof	2,89	1,75	4,82	3,15
3	Interior work	15,17	12,29	14,43	13,96
4	MEP installation	10,61	7,84	6,43	8,30
5	Finishes and closures	0,04	0,21	0,14	0,13
	Total	**29,56**	**22,50**	**26,55**	**26,20**

DISCUSSION

In this research we have analyzed the amount of film plastic waste generated in construction sites. To the best of our knowledge, this is the first research conducted that evaluates film plastic waste from construction site. Some previous studies have analysed the plastic waste, such as, Pericot et al., 2014; Pericot ja Merino., 2011; Häkkinen et al., 2014. However, their study included all type of plastic waste produced in construction sites (e.g., plastic pallets). Our research was solely focused on film plastic waste.

In our case projects, film plastic waste was collected separately onsite. According to Poon et al. (2001), building construction workers are hesitant to carry out on-site waste sorting that is considered to be time and labor demanding. A similar experience was shared in Percot et al.'s (2014) study indicating onsite segregation was around 1.80%. However, in our cases, the sorting rate was about 75% -- this is also mentioned in the project report (Lyytikäinen et al., 2020). It is mainly because in our case projects, film plastic containers were placed in multiple places, e.g., in every floor, yard and a larger film plastic waste container alongside other waste containers. Posters with instructions on waste sorting were stuck on the containers. Furthermore, cleaners were also instructed to correct the waste into the right container if necessary. For those reasons, segregation rate was higher in our cases.

Quantification of plastic waste for each activity is challenging. Pericot et al., (2014) emphasized that the suitable method would be to isolate the different waste categories generated in every activity. However, in practice, it is difficult to follow this procedure without disturbing the construction activities in multi-story residential buildings (Katz and Baum, 2011). To resolve this problem, we have adopted a task-intensity based approach. In this approach, we first analyzed the site activities and scaled them according to the amount of film plastic waste they could generate, in this research we refer that metric as intensity of the task. The intensity marking is discussed and validated with site personnel as well as in project meetings. Thereafter, all our case schedule's task were marked with intensity and evaluated accordingly.

After analyzing film waste amount for each activity, we created a database for film plastic waste produced in each activity of construction site. Based on the database, we developed a model, and it could be used to evaluate the amount of film plastic in future project for residential construction. This could ultimately help for better site waste management plan. Especially, it will help to figure out the size of the container to be placed as well as it will make easier for waste handling company for the frequency needed to pick up film waste which ultimately contribute to cut greenhouse gas emission somehow by avoiding unnecessary truck movement to the site.

Recently, plastic waste as threat to the environment is heavily discussed in academia, industrial professionals and the media. Many scholars discuss that the construction is one of biggest generators of plastic waste. However, there is no statistics available how much approximately amount of film plastic could be produced onsite and it would be necessarily making the waste management plan for the construction site. In this case, our database and model developed based on it, could contribute to develop the standard database, for instance, it could be used by statics Finland, Environmental Protection Agency, etc.

Overall, the findings from this study, specially kalvomuovi.fi platform, is an important initial step for removing plastic waste form construction site. As our platform would help to analyse the film plastic waste at the planning phase, which would help improve the site waste management plan. This would ultimately help to for implementation of Lean and green approach to the construction site.

CONCLUSION

To evaluate the amount of film plastic in construction site, we have evaluated three residential construction projects. To facilitate the most accurate possible measurement of film plastic waste, we have adopted the output method- so that we can measure the waste entering into the site as well as generated within the site. Based on our analysis, film plastic were collected from 1005-1710 kg (about 0,5-1,0 % of all waste) in our cases. The higher amount of plastic films were generated during interior Workstage. This includes the site activities requiring installation of more products e.g., furniture installation, partitions (More detail task level analysis, refer table 11).

Furthermore, while summarizing the analysis of our three cases projects, it showed that 33,64 kg film plastic waste was produced in every 100 m^2 and 26,20 kg was produced per apartment. Based on these results, we have developed a modelling tool that is able to evaluate the amount of film plastic in every work stage for the future projects.

During the site visit, the quality of the film plastic was also evaluated. Quality analyses were mainly based on: a) cleanliness and b) color / brightness. In our analysed cases, portion of the dirty film plastic was very low almost negligible, some cases have collected dirty film plastic in a same container as it used to collected film plastic whereas some have collected in discarded collect in the same container. In any case, the recycling company will clean the films before they process them. Similarly, it is also observed that the portion of non-color film was almost negligible. Thus, the authors did not apply strict rules about color while collecting film plastic.

At the end, based on case study results, the authors developed a platform called kalvomuovi.fi: that can be used to estimate the amount of film plastic waste in residential construction projects.

In this research, the authors analyzed only three cases and based on that, developed a model. For generalization, results from three cases may not be sufficient as the data sample could be considered thin. The model thus requires further testing to validate it for different cases. Also, all of the cases analyzed in this research were residential buildings, so the model presented will only be applicable for residential buildings. Further research is necessary to measure waste from other types of buildings (e.g., hospitals and schools.).

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GREEN IS GOOD: FIRST RUN STUDY OF A SUSTAINABLE BUILDING STRUCTURE

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ABSTRACT

The study made an account for in this paper is based on the hypothesis that introducing a climate-friendly building material to construction production may fundamentally impact project performance. In the paper, evidence is given for a prolonged, costlier process of erecting the building structure if an extremely low-carbon concrete combined with a 100 percent recycled aggregate is applied. Findings suggest various measures to be taken, to accelerate the hardening of the concrete. Otherwise, a positive environmental effect may easily diminish the overall project performance. The paper is based on a First Run Study (FRS) including a full-scale mock-up of a part of the building structure, including ground floor, wall, columns, and slab. As part of the study, data was collected about the temperature, firmness, and relative moisture of the concrete, and the effects of different actions applied to accelerate the hardening process. The impact of this study is an estimated risk reduction of 1,5 percent in the context of the project it was intended to support. The paper concludes that this type of experimentation should happen prior to actual performance to prevent construction projects from falling short of time and finances caused by unexpected results.

KEYWORDS

Lean and Green, First Run Study.

INTRODUCTION

In the first run study presented in this paper, an extremely low-carbon concrete combined with a 100 percent recycled aggregate is applied in a physical mock-up on site. The research carried out investigates whether – and under what conditions – it is feasible to use this substance in the building structure of a five-floor high, 11 000 square metres office building. The completed structure will be the first of its kind using this type of concrete to the full. To deliver the project is Veidekke, one of the largest general contractors in Norway. As part of its climate strategy, the company will reduce greenhouse gas emissions by 50 percent by 2030. An overview of emission sources from all building and civil engineering-related activities in the company shows that the use of concrete stands for as much as 31 percent of the total 269 000 tons of CO^2 emissions. Veidekke is also on the client side of the project, in companionship with OBOS, Norway's largest housing developer. Together, they have decided that the new-building project should at least contribute to a 50 percent reduction in greenhouse gas emissions. This makes it a primary concern to initiate changes that really make a difference in sustainable development.

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To prevent global warming beyond 1,5 °C above pre-industrial levels, the Intergovernmental Panel on Climate Change (IPCC) has concluded that greenhouse gas emissions must decline by 43 percent by 2030 and to net zero by 2050 (UN DESA 2022). Then being green, for lack of a better word, is good. Green here alludes to a mindset based on ensuring that activities, be they individual, corporate, or otherwise, reflect an overall concern for safeguarding the planet Earth and its natural resources. The construction industry generates about 38 percent of annual total greenhouse gas emissions globally (United Nations Environment Programme 2022). Size matters in this respect, the construction sector being one of the largest in the world economy, with about $10 trillion spent on construction-related goods and services every year (McKinsey Global Institute 2017). Furthermore, the cement and concrete industry is responsible for about 8 percent of global carbon dioxide emissions, more than double those from flying or shipping (Niranjan 2022). This means that, in the efforts to make a difference, the industry's attention needs to be drawn specifically to the emissions produced elsewhere and brought into construction production in form of building materials. The results presented in this paper can thus be of great value to an industry with a huge potential to turn the heating process on the planet down.

FIRST RUN STUDIES

First Run Studies were introduced by Ballard and Howell (1994) as a method to improve downstream performance, by changing how we do the work. The method is linked to craft operations and described as a process where the operation is examined in detail, where ideas and suggestions are requested from all parties, and experiments are performed to explore alternative ways of doing the work. The study ends with the definition of a performance standard, which in turn is challenged to meet or beat the best done thus far (Ballard and Howell 1994). A First Run Study reminds of the Plan-Do-Check-Act (PDCA) cycle, which was popularized by W Edwards Deming (Aguayo 1991). The cycle, also known as the Deming cycle, describes a simple method to test information before making a major decision. When running an experiment, the first step includes planning (or designing) the experiment, the next performing the experiment, and thereafter, checking the results by all the information gathered through the test, before acting upon the decisions based on those results (Aguayo 1991).

In the manufacturing industry, the concept of pilot production has evolved under somewhat the same line of reasoning as the PDCA cycle. Pilot production is typically applied to verify a new product and its production system. Almgren (2000), using the experiences of the Volvo Car Corporation, describes pilot production and manufacturing start-up as two processes that greatly affect development costs, time to market, and product quality. Pilot production refers to pilot runs carried out in a production system intended for commercial use. During pilot production, pilot vehicles are built and assessed from a product and production system perspective. Pilot production aims to identify and prevent disturbances affecting the final verification before the start of volume production (Almgren 2000). Manufacturing start-up is typically divided into two sequential phases, low-volume and high-volume production, where low-volume production is done to fine-tune the factors affecting performance before high-volume production (Almgren 2000).

In the IGLC conference proceedings, First Run Studies are scarcely represented. An interesting contribution to the topic is done by Tsao et al. (2000), which – even though it does not include a real first run – exemplifies the potential use of the method to prepare the installation of metal door frames at a prison project. In prisons, the door frame installation differs from the usual due to added security measures. The paper underlines that to improve the process of installing frames, different perspectives need to be considered. The authors conclude that this rarely happens, as all parties are seldom brought to the table to consider work structuring together early enough (Tsao et al. 2000). In the authors' view, thinking about system-wide solutions is also hampered by a contracting mentality. Instead of questioning a bad design, a worker complains and works around it, because their contracts are already signed, and work must proceed (Tsao et al. 2000). A few years later, altogether three real First Run Studies are presented to the IGLC by Saffaro et al. (2006), to investigate the role of it as an experimentation technique. The authors conclude from these studies that production constraints typically interrupt a proper application of the cycle observation-reflection-action, thus leading them to question the capacity to deal with prototyping issues in a dynamic environment (Saffaro et al. 2006).

Construction production, it seems, is not very suitable for experimentation. Koskela (2000) has a somewhat alternative perspective, seeing the actual building as a prototype where the production stage is used to eliminate errors generated in the design or production planning processes. Does this mean every construction project is a first-run exercise? To the point it is, Saffaro et al. (2006) suggest that virtual models must be used to eliminate design uncertainties and errors, thereby removing product-related problems that do not allow the prototyping exercise to focus on work methods and standards. At the same time, production in construction is always locally bound and dependent on physical factors such as soil and weather conditions (Vrijhoef and Koskela 2005). While virtual models, most certainly, are helpful to reduce design uncertainties and errors, they cannot replace the transformation of the design into physical reality which must still rely on the use of physical mock-ups (Pietroforte et al. 2012).

METHOD

The First Run Study was carried out, using a combination of laboratory testing and a physical mock-up. In addition, a digital model was developed to visualize all the planned actions to be taken on different parts of the physical mock-up. The laboratory testing was carried out to test different combinations of concrete, specifically focusing on the effects of using a recycled versus a normal aggregate. The physical mock-up was erected in situ, at the exact same site as the later office building is being built. The mock-up was done in the winter to test how the extremely low-carbon concrete responded to low-temperature exposure.

1. The digital model was used:
    a. To make a visual representation of the physical mock-up
    b. To identify which actions should apply to various parts of the physical mock-up
    c. To do quantity calculations and take-offs from the model, as part of planning the structural work
2. Laboratory testing was necessary:
    a. To test the elasticity, firmness, and relative moisture of the concrete combined with the use of the recycled aggregate
3. Use of the physical mock-up allowed:
    a. To collect reliable data about the concrete and structure
    b. To include air temperature in the evaluation
    c. To measure the effect of different actions, on the hardening process

For the testing performed in the laboratory, different tools were applied. To test the elasticity of the concrete, fresh concrete was poured into small, cubic-formed containers which in turn were exposed to vibration. To test the concrete's firmness, the cubes were later exposed to pressure using a manometer to measure the megapascal. To measure the relative moisture in the concrete, a moisture meter was applied.

A physical mock-up was erected, about 100 m² in size, and including 27 m³ of concrete. The building structure was cast in place, using post-tensioned reinforced slabs. Every cast was monitored, using concrete sensors to measure the temperature, strength, and maturity of the concrete. Several actions were applied to accelerate the hardening process, amongst others including heating pipes containing glycol, hot air fans, infrared ovens, insulation plates, surface accelerators, polyethylene foam, and heating cables.

RESULTS

THE RECYCLED AGGREGATE

The laboratory tests were done partly to find out more about the quality of the recycled aggregate, partly to investigate the effects of using it in fresh concrete, and partly to study how the concrete appears when using 100 percent recycled aggregate.

The quality of the recycled aggregate was controlled using several measures, amongst others to check the density and variation in the size of grains, their ability to absorb water, and their chemical composition. This is because the quality in turn will determine how the concrete appears. The control checks uncovered that the recycled aggregate had much the same quality as virgin aggregates.

To test the workability of the fresh concrete, a slump was poured into a funnel-shaped form which was pulled up to measure how much the substance floated (Figure 1). Thereafter, E-module testing was done on concrete cylinders (Figure 2), including the use of equipment to measure (and regulate) the elasticity of the concrete.

Figure 1: Controlling the workability of the fresh concrete

Figure 2: E-module testing

THE PHYSICAL MOCK-UP

The physical mock-up was erected in Oslo, Norway, in February-March 2021. The middle temperature in the area is then -2 °C. The timing was decided because the weather was an important parameter to include in the tests. To control for variations, the outdoor temperature was logged on a regular basis. The structural work, including the ground floor, supporting walls, columns, and slab, was a replica of a part of the office building later to be built. After all the tests were completed, the mock-up was demolished.

The ground floor

The ground floor was divided into four fields, to which different actions were applied to be able to control their effects (Figure 3). Field 1 included the use of a surface accelerator and covering up by using polyethylene foam directly after the cast. The cast was done directly on the gravel. Field 2 included the use of insulation underneath the cast, membrane curing, and covering up when the cast was ready to walk on. Field 3 included the use of heating pipes, membrane curing, and covering up when the cast was ready to walk on. The cast was done directly on the gravel. Field 4 included the use of insulation underneath the cast, heating pipes, membrane curing, and covering up when the cast was ready to walk on.

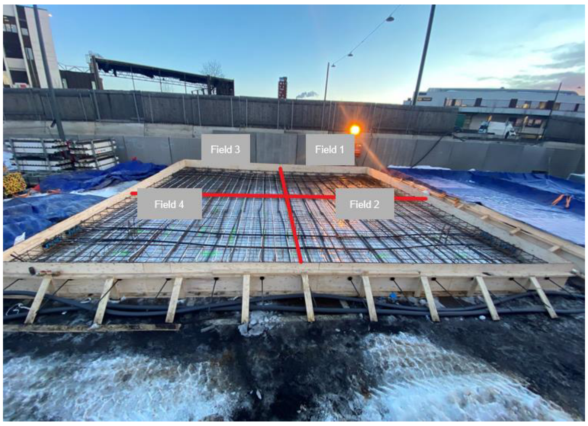

Figure 3: The ground floor, including the four fields

Findings related to the ground floor (Figure 4) show that the temperature in the fresh concrete drops heavily, especially in field 1 which include only limited actions and where the cast is done directly on the gravel. This has to do with the extremely low-carbon concrete, which develops no heat of its own. Thus, if the cast goes on in the winter, actions will be necessary to avoid a drastic temperature drop. Of all the actions applied, the most effective combination seems to be the one used in field 4 with insulation underneath the cast, heating pipes, membrane curing, and covering up when the cast is ready to walk on. The temperature development in the concrete affects the hardening process. As a result of the extremely low-carbon concrete being a “dead” substance, the hardening process is delayed and occurs only after 20 hours or more. When measured in megapascals, it takes about 24 hours for the ground floor in fields 2 and 4 to have reached an acceptable level of strength (5 megapascals). From the findings, one may conclude that especially heating pipes and insulation appear to boost the hardening process.

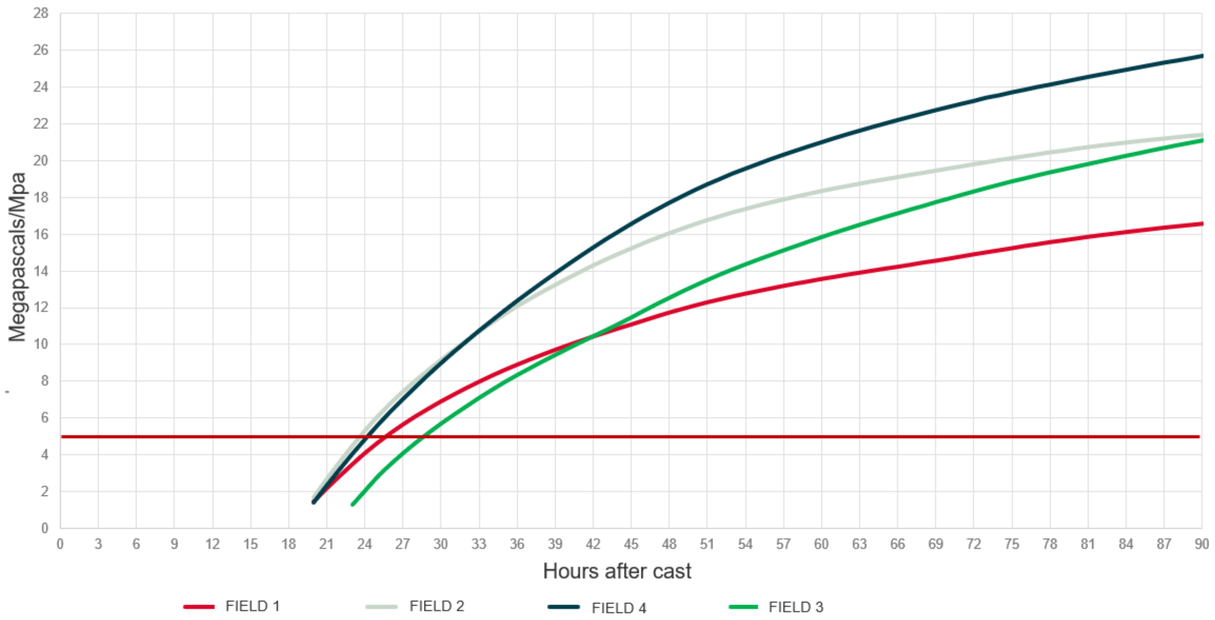

Figure 4: Hardening process of the ground floor

The columns

Altogether four columns were included in the mock-up. Different measures were applied to each of them (Figure 5). Column 1 was insulated by a double layer of polyethylene foam, while column 2 had only one layer of insulation. Column 3 had heating cables included in the concrete, in addition to one layer of insulation. Column 4 had heating cables on the outside, underneath one layer of insulation.

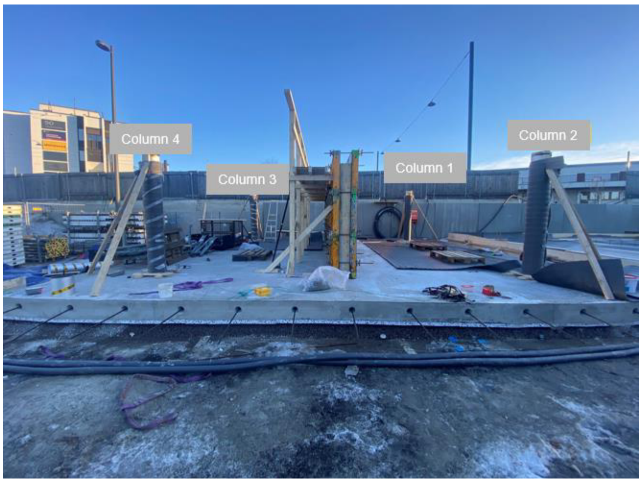

Figure 5: The four columns

Heating cables, either in the concrete or on the outside, seem to have a positive effect on the hardening process. For the two columns including this measure, it takes about half the time to reach the acceptable level of strength (8 megapascals) compared to the columns with only insulation.

The wall

The wall surfaces were split in two, where the upper parts included no measures while the lower parts included subsequently heating pipes containing glycol on one side and heating cables on the other (Figure 6).

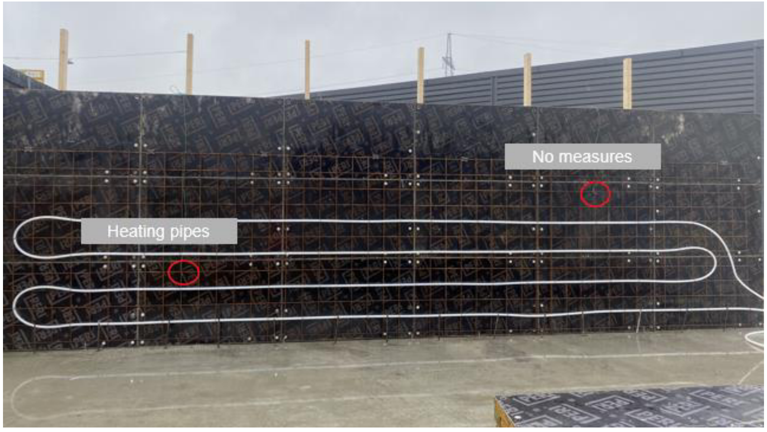

Figure 6: Wall surface, including heating pipes

The temperature development indicates a sudden and steep effect of both heating options. Furthermore, the hardening of the wall using heating cables or heating pipes seems to be all the same, both requiring between 15-18 hours to reach an acceptable level of strength (5 to 8 megapascals). In comparison, around 30 hours or more are required before the same level is reached when no measures are used.

The slab

Four different measures were tested to improve the hardening of the slab, which moreover was divided into several fields. The most comprehensive method applied was where the area underneath the slab was covered by insulation and hot air was pumped into it and circulated (Figure 7). Other actions underneath the slab included the use of infrared ovens and insulation plates, whereas heating pipes were tested in the slab.

Figure 7: Slab, with hot air underneath

Findings indicate that heating pipes in the slab are the most effective solution among those tested to improve the hardening process (Figure 8). Applying this measure, it takes 38 hours for the slab to reach the acceptable level of strength (25 megapascals). It also appears to give good results if insulation plates are used underneath the slab. On the opposite side, if no actions are taken underneath or in the slab, it may take 100 hours or more for the slab to reach the acceptable level of strength.

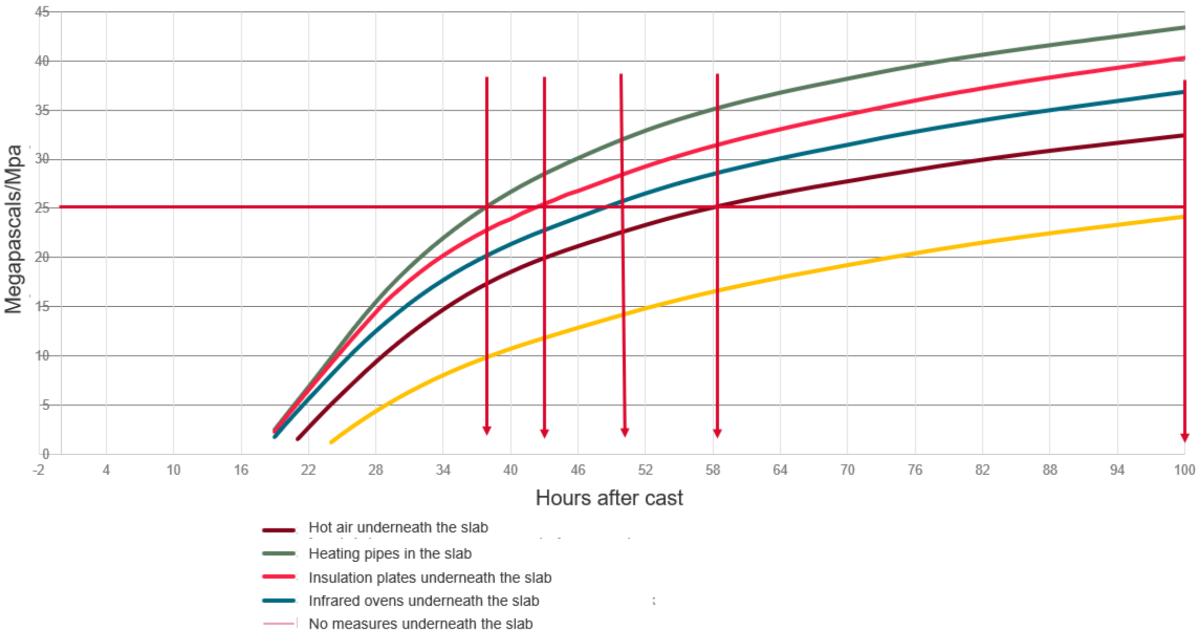

Figure 8: Hardening process of the slab

DISCUSSION

If using extremely low-carbon concrete, what would be the ideal measures to apply to improve the hardening process when erecting the structural envelope? Based on the results presented in this paper, different measures seem to apply to the various elements. Regarding the ground floor, the most effective combination is when insulation is placed underneath the cast, heating pipes in the cast, membrane curing, and covering up when the cast is ready to walk on. On the columns, heating cables on the inside or the outside have a positive effect. As for the wall, somewhat the same can be said about heating pipes and cables, whereas in terms of the slab heating pipes in the concrete seems to give the best results. On the opposite side, if no actions are applied using extremely low-carbon concrete, the findings presented here indicate a late hardening and substantially prolonged structural building phase. This is because the extremely low-carbon concrete develops no heat of its own. When having to deal with this substance, the simple answer to the question above is thereby to make use of all these actions.

Following this First Run Study is the office building constituting 11 000 square metres and consisting of 3900 m³ of concrete. While there is no calculation of the total costs of applying all the measures described, it will inflict additional expenses on the project. This would necessarily mean that the client needs to find it appropriate to spend the extra money. From a client's perspective, the cost of doing it will naturally be weighed against alternatives. For instance, how much will the project be delayed if no measures are used, weighed against the potential time savings of applying them? All the actions considered; this question seems particularly relevant to address to those meant for the hardening of the slab. If no or only simple measures are applied here, it takes a minimum of 100 hours before the slab has reached an acceptable level of strength (25 megapascals). A hardening process thus long would substantially delay the production progress.

This moreover triggers another consideration related to which actions should be prioritized if the focus was on choosing one or a few that would be the most effective. The actions meant for the slab seem particularly relevant in this respect. At the same time, all the rigging and equipment needed to apply at least some of these actions brings the cost concern into the equation. Then, the use of insulation plates underneath the slab might be the optimal choice. Even though heating pipes in the slab are slightly more effective in terms of hardening, it is also more expensive. Not necessarily due to material costs alone, but because of the power supply needed to be combined with the use of the pipes. At the same time, if the outdoor temperature falls drastically – which might very well happen in Oslo in February – then using heating pipes is likely the best alternative, even though applying it may cost more.

What if the process of erecting the structural envelope goes on in the summer instead of winter? Considering that extremely low-carbon concrete develops no heat of its own, it would seem a plausible strategy to do the cast in a period of the year when a much warmer atmosphere could help the hardening process go faster. What is more, it would save the project from additional expenses due to the various actions discussed above. Even more so, it would save the environment from emissions at the construction site, in form of material waste and energy consumption caused by the actions described. Since the mock-up was erected in the winter, there is no data to describe the effects of doing the cast at another time of the year. That said, the main problem seems to be the lack of heat inside the concrete, which delays the hardening process. Furthermore, when the substance is exposed to heat from external factors, it exhibits a positive response in terms of a more rapid hardening. After all, what can be more environmentally friendly than using the sun's warmth to make this happen? Ultimately, the solution must be to do the cast in the summer period if extremely low-carbon concrete is used.

Given the ultimate solution listed above, was the physical mock-up and all the testing a waste of time and money? No, because insight beats hindsight. Due to the use of a new substance, risks in the project's uncertainty analysis carried out were considered particularly high for the structural building phase. As a result of the first run study, the project's uncertainty was reduced from 4 to 2,5 percent of the total contract sum on 410 MNOK. A pilot production costing approximately 1,5 MNOK thereby paid off several times as uncertainty dropped from 16 to 10 MNOK.

CONCLUSION

This paper gives support to the hypothesis that introducing a climate-friendly building material to construction production may fundamentally impact project performance. Evidence is given for a prolonged, costlier process of erecting the building structure if an extremely low-carbon concrete combined with a 100 percent recycled aggregate is applied. A First Run Study (FRS) involving a physical mock-up proved very useful to uncover which actions are the most effective to accelerate the hardening process. The impact of this study was an estimated risk reduction of 1,5 percent in the context of the project it was intended to support. This type of experimentation should happen prior to actual performance, though, to prevent construction projects from falling short of time and finances caused by unexpected results. The outcome of this study is knowledge about how extremely low-carbon concrete appears in cold conditions. Without it, it would be less obvious that cast in the summer has clear-cut advantages. In fact, one can even imagine that cast in the winter could be initiated without further hesitations, with potentially devastating results. Additionally, while it is clear and obvious that doing the cast in the summer is the best alternative, this is not always a choice. A construction project evolves at the mercy of many conditions, whereof some are more difficult to control than others. To reach a timing in every project that fits perfectly with a schedule saying that the cast should only go on in the summer is a very naïve approach to handling the problem. Rather, it would seem a more passable way to go, to learn from the First Run Study presented in this paper which actions seem most appropriate to apply in your project and avoid experimenting too much once the production gets going.

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EXPLORING HOW LEAN PROJECT DELIVERY SUPPORTS CARBON CAPTURE, UTILIZATION, AND STORAGE FOR INDUSTRIAL RETROFITS

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ABSTRACT

The "lean construction ideal" is to maximize stakeholder value, minimize waste, and emphasize collaboration throughout the design, construction, and operating stages of a building project. In practice, lean construction relies on methods such as the Integrated Project Delivery (IPD) system to align stakeholder interests and share risks throughout the project lifecycle. IPD effectively enfranchises various project stakeholders as parties to one agreement, integrating their involvement throughout the design and construction process. While lean construction methods are evidenced to enhance project efficiency in cost and schedule while improving quality, the collaboration fostered by IPD also creates a project environment conducive to innovation and the adoption of new technologies. To that end, lean construction environments, and IPD projects in particular, may offer an opportunity to increase the adoption rates of more environmentally-conscious design alternatives, particularly as the construction industry continues to trend in a more sustainable direction. This paper explores how the lean project delivery system supports incorporating innovative design options on retrofit construction projects (i.e., on existing facilities), and leverages incorporating carbon capture, utilization, and storage (CCUS) systems on cement plants as a proof of concept.

KEYWORDS

Sustainability, environment, collaboration.

INTRODUCTION

Literature from the International Group for Lean Construction (IGLC) confirms that often, the leanest path to "green" is to retrofit an existing building rather than demolish it and begin from scratch (e.g., (Ladhad and Parrish 2013; Ding and Parish 2019; Soliman-Junior et al. 2022). Research from outside of lean construction further supports this claim. For example, Jagarajan et al. (2017) discuss the need to retrofit the existing stock of buildings and industrial facilities in order to achieve climate goals. Perhaps more relevant to this study is the nexus of lean and green shifts within manufacturing processes and facilities, e.g., Huang et al. (2022), a study that discusses the necessity of retrofitting manufacturing plants, equipment, and processes to ensure that production is as lean as possible (i.e., minimal labour, material, and time waste) and that the manufacturing process limits environmental impact to the extent possible. Mellado and Lou

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(2020) discuss the importance of lean project delivery systems for creating an environment where sustainability can thrive; they argue that leveraging building information modelling in a lean project team with sustainability goals is the best environment for BIM, lean, and sustainability goals to be achieved. This paper, similarly, argues that a lean project delivery system, and a team committed to lean, provides the right environment for green retrofits, and CCUS retrofits of cement plants specifically.

BACKGROUND

Lean Project Delivery System

Figure 1Figure illustrates the lean project delivery system, first introduced by Ballard (2000), and updated in 2008 (Ballard 2008). This system illustrates collaboration across project phases (i.e., project definition, lean design, lean supply, lean assembly, and use) as well as across project stakeholders, evidenced when triangles for different phases overlap, i.e., the "Design Concepts" node represents collaboration of owner representatives, designers, engineers, and contractors involved in project definition with the stakeholders involved in lean design. Such a system supports implementation of lean throughout the project lifecycle.

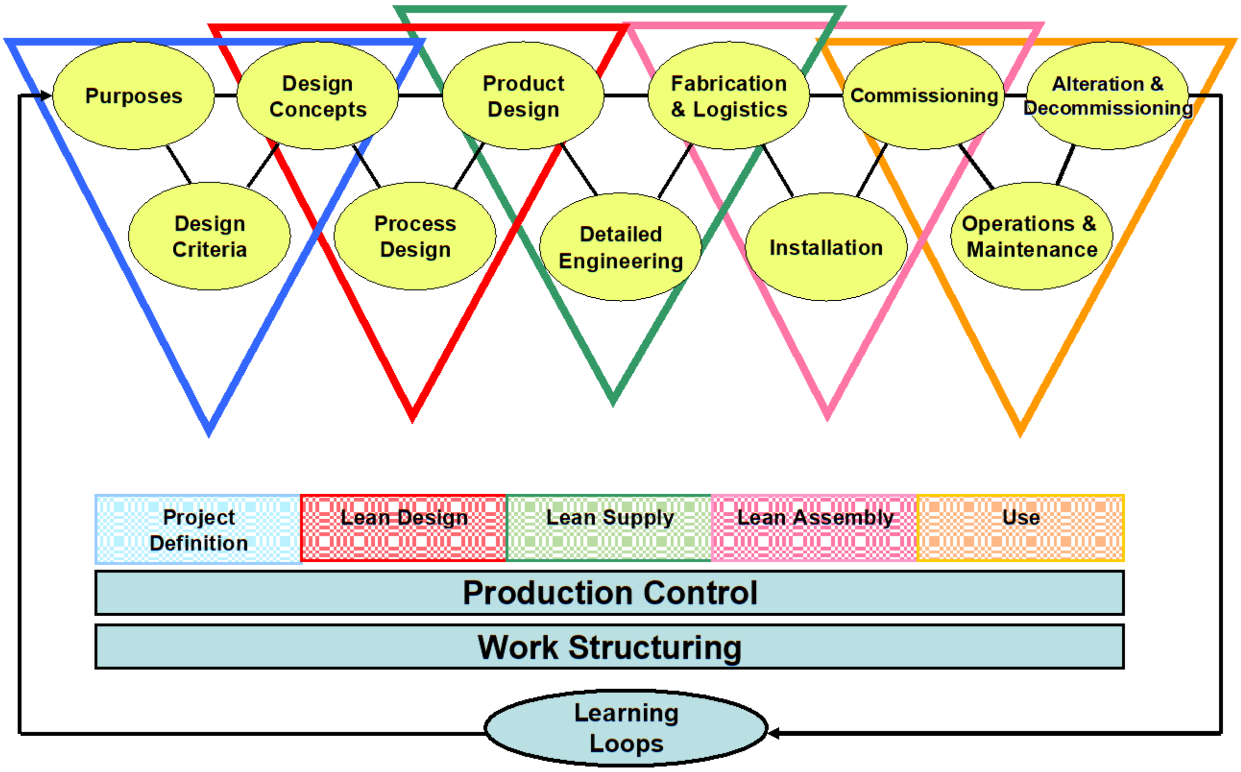

Figure 1: Lean Project Delivery System (Ballard 2008)

CCUS

Carbon Capture, utilization, and storage, or CCUS, refers to technologies that capture CO_2 from large point sources, i.e., industrial facilities, and then transport and utilize or store the CO_2 (IEA 2023). The number of retrofit construction projects involving CCUS installation will increase substantially over the next ten years. By the end of 2021, the global CCUS project pipeline contained 135 facilities, including 27 fully operational plants (Global CCS Institute 2021). The pipeline contained 51 facilities in 2020, with 21 operational (IEA 2023). Attaining the climate goals of the 2015 Paris Agreement requires construction of an additional 70-100 CCUS facilities globally, each year (Global CCS Institute 2021). CCUS represent the only group of technologies which at once abate end-of-pipe carbon emissions and offset past emissions. Given their capture capacity per area, CCUS technologies are the most direct path to a negative carbon effect.

For this reason, CCUS features prominently on sustainability roadmaps to net-zero and beyond (e.g., (GCCA 2022). Attaining net-zero in hard-to-reach sectors like power generation or cement and steel production is virtually impossible without CCUS technologies. Reflected in their sustainability commitments, Heidelberg Cement's carbon neutrality roadmap (Lenz 2023) features immediate and widespread integration of carbon capture technologies to reduce cement process emissions followed by intense development of capture and utilization technologies (Lenz 2023). Heidelberg showcases the retrofit of the Heidelberg Materials cement plant in Brevik, Norway as a first of a kind full-scale carbon capture demonstration (Brevik CCS 2023).

RESEARCH HYPOTHESES

Based on the background presented above, the authors developed the following research hypotheses:

- The collaborative nature of lean project delivery supports project teams' ability to implement CCUS technologies in industrial facility retrofit projects
- The lean project delivery system supports inclusion of innovative design alternatives in retrofit construction projects

METHODS

Testing the aforementioned hypotheses would require exploring a large number of "similar" retrofit projects, some delivered via LPDS and others not. Ideally, in order to conduct tests for statistical significance between the projects delivered with LPDS compared to those delivered without it, the authors would collect at least 30 projects delivered with each delivery system, for a total of at least 60 projects. Given that the total number of fully operational CCUS plants at the end of 2021 was 27, such a study is not feasible at present. Moreover, not all of the 27 operational plants represent retrofits, adding further difficulty to this experimental approach.

Given the limitations outlined above, the authors opted instead to illustrate how LPDS *could facilitate* the inclusion of sustainable design alternatives in retrofit projects. More specifically, the authors explore how the LPDS environment supports inclusion of one such sustainable design alternative, CCUS. To do so, the authors present the barriers to CCUS technology implementation and discuss how lean project delivery, and lean tools may be able to address these barriers. The barriers themselves are derived from a recent interview study conducted by the first author. The authors then suggest lean tools that may address these barriers based on IGLC and other lean construction literature.

INTERVIEW PROTOCOL

The authors developed the interview protocol to elucidate barriers in 2021 (Table 1), and conducted interviews from April 2022 – December 2022. The authors map each question to the most applicable phase of the LPDS, in order to best contextualize results.

The authors conducted interviews with 21 practitioners that spanned fields of basic research, applied research, technology development, innovation management, life-sciences, geophysics, civil engineering, construction materials, cement and concrete technologies, energy infrastructure, and innovation policy. The authors were transdisciplinary in their approach so they could learn about how innovative and sustainable design alternatives were developed and deployed in the cement industry. As important, they could understand the science that underpins CCUS technologies and how these scientific considerations impact CCUS adoption in the cement industry (e.g., how the chemical process of producing cement impacts the feasibility of deploying various CCUS technologies in cement plants).

Table 1: Interview Protocol

Number	Question	LPDS Phase
1	What types of new cement materials or technology have you worked with and how often do you work with them?	Lean Design
2	What needs to improve for the cement materials and technologies in use today?	Lean Design
3	What are some of the drawbacks of the green cement materials and technologies you have worked with so far?	Lean Design
4	What project delivery methods are best suited for green/regenerative projects or projects with novel technologies?	Lean Assembly
5	What are the impacts to cost (budget/schedule/productivity) when a new cement material or technology is brought on to a project?	Lean Assembly
6	What are the risks and benefits for taking on regenerative/green projects?	Project Definition
7	What innovations are most successful in the cement industry?	N/A
8	What innovations are most needed in cement materials and technologies?	N/A
9	When considering an innovation portfolio decision, what data and inputs are most useful?	N/A
10	What barriers do you perceive to innovation with cements and what would you suggest to overcome them?	N/A
11	What makes a regenerative or green innovation easier to adopt or spread within the industry?	N/A
12	What effect do sustainability and climate goals have on shaping your innovation portfolio?	Project Definition

All interviews were conducted via zoom. Interviews were recorded with the participant's consent (all participants consented to being recorded). The authors used the zoom transcripts for coding (Frey and Fontana 1991; Wengraf 2001). Specifically, the authors coded the responses for themes related to barriers to adopting innovative technologies in the cement industry. For the purposes of this paper, only barriers related to CCUS are presented.

RESULTS

Based on the interviews, the following barriers to CCUS implementation in the cement industry emerged:

Limited utilization potential for captured CO_2: Participants indicated that finding a local use for captured carbon was a challenge to achieving circular economy. Moreover, responses indicate that natural processing of CO_2 seems to favour storage, e.g., carbon deposits under the ocean floor.

Evaluation of technology readiness can impede implementation: Respondents discussed the Technology Readiness Level, or TRL, which influences those technologies that can be, and are, considered for inclusion in a capital project. In the context of the cement industry, the technologies with high TRL may not yet be cost effective over the expected lifetime of the plant.

Indeed, traditional cost assessments and their analytical methods do not accurately depict risks, costs, and benefits of CCUS projects in current and future markets. These evaluation models assess the cost of a CCUS install as a function of capital expenditures (CAPEX) and effects on operating costs (OPEX), accounted for in cost per unit of CO2 captured. Analysis includes baseline assumptions about the operating requirements of the carbon capture equipment, such as power requirements, maintenance, cost of compression, transport, and storage, and effects on plant productivity during and after construction (e.g., (Liang and Li 2012). Baseline assumptions rely on outdated performance data, typically from amine-based capture processes relying on coal-fired heat and power generation with overstated power requirements and carbon capture efficiencies around 70 to 80% of total plant emissions (Liang and Li 2012). Assumptions also incur oversized effect to indirect costs, such as technology readiness level (TRL) impacts on contingency planning costs (Gardarsdottir et al. 2019) and production impacts from simulated process flow models (Liang and Li 2012). Outside-the-gate factors assume fixed estimate rates for variable factors like future carbon pricing and energy supply types (Liang and Li 2012). Traditional assessments may also ignore market specific conditions like the availability of carbon transport and storage infrastructure or potential revenues for captured CO2.

Cement plants that are “new” are less likely to undergo an intensive retrofit: Given the relatively young age of cement plants discussed by interviewees, the interviewees indicated that taking on a capital-intensive retrofit would be unlikely unless such a retrofit was mandated by a local/state/national policy.

Cement plants have typical service lives of 30 to 50 years (Gardarsdottir et al. 2019). With the average age of plants in the U.S. at just under 20 years (IEA 2023), many existing plants could be considered for potential CCUS retrofit, provided they can sustain operations for the 20 to 25-year payback period (Gardarsdottir et al. 2019). CCUS installation can raise the costs of clinker production 50-90% (Gardarsdottir et al. 2019). The cost of captured carbon is a function of the cost of clinker divided by the total capture capacity of CO2 emissions. Cost of captured carbon varies widely according to the capture efficiency of each technology and the specific plant deploying it (Gardarsdottir et al. 2019). Total plant costs with carbon capture compared to potential revenues and incentives in each market determines the economic justification for retrofit.

DISCUSSION

The authors discuss herein how the barriers listed in the "Results" section can be addressed by lean project delivery.

LIMITED UTILIZATION POTENTIAL FOR CAPTURED CO_2

It is not immediately clear how lean tools, or the lean project delivery system, can address this barrier. However, one possibility would be to conduct a root cause/5 Whys analysis to understand exactly why the utilization potential is low. The authors do not expect that this analysis will yield a clear solution. Rather, the authors posit that this analysis will clearly frame future research directions that provide clarity about what makes utilization difficult. For instance, is the issue that there is not enough demand for CO_2 in the marketplace? This would seem reasonable, as many ongoing efforts work to reduce the CO_2 created, rather than use CO_2. If this is the root cause, then perhaps solutions for CCUS should focus more on storage of the captured carbon, without trying to develop a case for using the CO_2. If, however, the issue is that once carbon is captured, the transport to the utilization site (e.g., a soda plant) "costs" more CO_2 emissions than the CO_2 capture and utilization avoid, there is a clear opportunity to site new users of CO_2 proximate to cement plants with CCUS technologies installed. Indeed, the authors research suggests that if CO_2 has to be transported more than 100 km, the net CO_2 emissions are higher than if the CO_2 had simply been released at the plant.

EVALUATION OF TECHNOLOGY READINESS CAN IMPEDE IMPLEMENTATION

As discussed, evaluation of technologies and their applicability for a given plant should not be considered "one size fits all." Lean philosophies recognize the unique nature of construction sites and support developing the best approach for that specific site. Of particular note for evaluation is set-based design (e.g., (Ward et al. 1995; Sobek et al. 1999; Rekuc 2005; Parrish et al. 2007; Parrish et al. 2008a; Parrish et al. 2008b; Parrish 2009), which allows project teams to consider multiple design options longer than would be typical in a point-based design scenario. For the case of CCUS retrofits for cement plants, set-based design may involve considering multiple CCUS technologies, regardless of their technology readiness level. Indeed, the goal would be to allow each CCUS technology to persist in the design process until the last responsible moment, when failure to make a decision delays the overall project (Parrish et al. 2007). Project teams may elect to consider various CCUS technologies and explore their fitness for the cement plant at hand, in terms of leveraging incentives, meeting local/state/national or organizational CO_2 emissions reduction goals, and supporting site-specific production cost metrics, e.g., $\$/t_{CO2}$. When design alternatives are developed, project teams can make data-driven decisions about which CCUS technology is most appropriate using Choosing By Advantages (e.g., (Suhr 1999; Parrish and Tommelein 2009; Arroyo et al. 2015). CO_2 emissions reductions can be expressed as a 'must' or a 'want' criterion, depending on the requirements of the city or region where the plant is located.

NEWER CEMENT PLANTS ARE UNLIKELY TO UNDERGO A RETROFIT

The "Project Definition" and "Lean Design" phases of the LPDS offer clear opportunities to address this barrier. While it is understandable that a cement plant owner may not want to make a large capital investment in their relatively new plant, climate-related legislation and goals may warrant making such investments earlier than originally planned. Similar to the "evaluation barrier" described above, this barrier can be addressed by thoroughly understanding the context for the project. Assuming that a plant *must be retrofit* to comply with internal or external CO_2 emissions reduction plans, then lean project delivery offers the full project team an opportunity to collaboratively brainstorm potential solutions and assess them as a team. To address this barrier, a "big room" may be helpful (Ballard 2008). However, instead of using the big room during the design phase, the authors recommend implementing a big room meeting during an ownership meeting; that is, the plant owners could invite multiple designers and engineers to one of their routine meetings where they discuss plant operations. This big room would essentially offer a platform for brainstorming feasible CCUS solutions for each plant in the owners' portfolio. Then, the project teams can leverage set-based design and Choosing By Advantages to evaluate the most appropriate CCUS option for each site.

BROADER CONTEXT: EXISTING FACILITY RETROFITS

While this paper has focused on the barriers to implementing CCUS in cement plants, the barriers are likely not all that different than barriers facing any facility retrofit. As concern about the climate grows, and policies begin to be implemented that limit CO_2 emissions and mandate energy performance across sectors (e.g., (State of California 2018; New York City 2019), many facility owners will face a need to retrofit their facilities. The LPDS, and specific tools that enable it, can help owners identify the appropriate potential retrofits for their facility and decide from among these alternatives.

CONCLUSIONS

This paper explored how the lean project delivery system can support CCUS implementation in the cement industry. The authors highlighted specific barriers to CCUS implementation in the current marketplace, including limited utilization potential for CO_2, evaluation of CCUS technology, and unwillingness to invest in a relatively new asset. The authors discuss how the LPDS, and lean tools like set-based design, Choosing By Advantages, and big room meetings can help owners to overcome barriers associated with CCUS implementation. Indeed, the authors argue that these results extend beyond CCUS implementation in cement plants, and extend to any facility that requires a retrofit.

As discussed in the "Methods" section, the authors did not have enough data about enough projects to compare project outcomes for those projects using the LPDS versus those that did not. Such a study would be welcome in future research by the IGLC community.

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THE CIRCU-LEAN REVOLUTION: A REVIEW OF THE SYNERGIES BETWEEN LEAN AND THE CIRCULAR ECONOMY

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ABSTRACT

Due to the impacts of industrialisation on the planet's environmental systems, industrial practice has had to evolve. Sustainable development goals have been set by the United Nations to limit industrial impacts on the environment. At the core of the development goals are the efficient use of materials and the reduction of waste. Two common production philosophies are becoming prevalent within the literature as a solution to consumption and waste within the construction industry, Lean and the Circular Economy (CE). Both provide aspects of green supply chain management that are required to meet the goals set by governments. There are clear synergies between the two philosophies though there are few investigations into their likeness within the literature. This paper aims to further investigate the synergies between Lean and the CE within the construction industry to develop the extant body of knowledge. The findings of the research identified that the majority of interactions between the concepts were positive although not entirely explored in construction. The core similarities surround waste reduction whereas the key differences are Lean's human management and the CE's closed-loop value retention. Therefore, it is suggested that a complimentary mixed Circu-Lean philosophy will be the future of production and construction.

KEYWORDS

Lean Philosophy, Circular Economy, Circu-Lean, Construction, Built Environment

INTRODUCTION

Since the early innovations of man, the analysis of the economic system and its activities have brought forth knowledge for the advancement of the production process. Revelations in economic and production theory have revolutionised countries and humanity's way of life. Allowing production activities to produce higher quantities, higher quality, and in a shorter timeframe (Liker, 2004; Ghisellini *et al.*, 2016). By increasing these aspects of production, economies, and organisations have created competition for the best system structure (Shah and Ward, 2003; Liker, 2004). The creation of Mass and Lean production proposed differing

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philosophies which focus on aspects of the supply chain in order for improved outcomes such as quantity or value (Liker, 2004). Since the late twentieth century, the rhetoric has refocused on the impacts of the economy on organic life and the biological systems that support it (Huovila and Koskela, 1998; McDowall *et al.*, 2017; Ogunmakinde *et al.*, 2022). This is due to the analysis and understanding of the environmental impacts produced by economic activities. The results of which identified an unsustainable future for humanity without industrial change. Sustainable development goals set to limit the impact of humanity's expansion have been created by the United Nations (UN, 2022). The targets set by the United Nations commonly aim to reduce the number of resources consumed and the wastes concurrently produced in the development and maintenance of economies (UN, 2022). In this effort, the improved management of resources within the construction industry is proposed through waste-focused production philosophies and Supply-Chain Management (SCM) (Carvajal-Arango *et al.*, 2019; Hossain *et al.*, 2020; Ogunmakinde *et al.*, 2022).

Green Supply Chain Management (GSCM) is becoming more popular within academic literature (Kalemkerian *et al.*, 2022). In the development of a green philosophy of production to reduce waste, the benefits of Lean production in reducing waste and environmental impacts were identified (Huovila and Koskela, 1998; Marhani *et al.*, 2013; Carvajal-Arango *et al.*, 2019). The Lean philosophy's promotion of value through the reduction of waste in all its forms has provided a basis for green production. However, a more recent philosophy has grasped similar attention for the reduction of waste within the economic supply chain, the Circular Economy (CE) (Adams *et al.*, 2017; Geisendorf and Pietrulla, 2018; Chen *et al.*, 2021). The CE production philosophy creates a closed-looped flow of materials within the supply chain (MacArthur, 2013). The value of the original material input is the core focus of the philosophy and is therefore maintained throughout the supply chain (MacArthur, 2013). Thus, the CE reduces waste through the informed design and conservation of resources (Benachio *et al.*, 2020). Both the Lean and CE philosophies of production reduce waste within the supply chain to meet the demands of a modern sustainable industry. However, the synergies between the concepts are scarcely investigated in the literature with publications only appearing from 2021 (Benachio *et al.*, 2021; Schmitt *et al.*, 2021; Silva *et al.*, 2022). Furthermore, publications specifically looking at the synergy between the two concepts within the construction industry is limited to one pertinent journal publication by Benachio *et al.* (2021). This gap in knowledge requires addressing though as of yet the extant knowledge is yet to be coalesced. This paper aims to investigate extant literature surrounding the synergies between Lean and the CE within both manufacturing and the construction industry to coalesce and contrast current knowledge to guide future investigations into the synergies within construction.

RESEARCH METHODOLOGY

The research conducted was in the form of a systematic literature review, in which data was collected using Scopus, Web of Science, and Google Scholar by using keywords to search for the titles, abstracts, and keywords of extant literature. The following keyword strings were used; **String 1 (CE):** ("Circular Econom*" OR "Circular Practice" OR "circular manage*") AND ("construction industry" OR "construction" OR "built environment") ; **String 2 (Lean): (**"Lean Philosophy" OR "Lean Production" OR "Lean Principle") AND ("construction industry" OR "construction" OR "built environment"); **String 3 (Synergies) (**"Circular Econom*" OR "Circular Practice" OR "circular manage*") AND ("Lean Philosophy" OR "Lean Production" OR "Lean Principle"); **String 4 (Synergies in Construction): (**"Circular Econom*" OR "Circular Practice" OR "circular manage*") AND ("Lean Philosophy" OR "Lean Production" OR "Lean Principle") AND ("construction industry" OR "construction" OR "built environment"). Twenty papers were identified for String 3 and five papers were identified for String 4 within the literature, String 1 and 2 have large bodies of extant literature from which only core literature had to be selected for context. The sampled papers were manually reviewed and excluded if they were not a journal article or were deemed irrelevant to the research or of a low quality. The final sum of papers for String 3 and 4 included eight journal articles on the synergies between the two topics, four of which were construction related. An interpretivist philosophy and deductive reasoning guided this study to review and compare the synergies within the literature (Saunders *et al.*, 2009). The selected literature from String 4 was analysed through content analysis to identify the core principles of the two concepts and their synergies (Saunders *et al.*, 2009; Patton, 2014). A qualitative research synthesis analysis was conducted to compare and contrast the results of the literature on the synergies using a matrix of the identified synergies within literature (Patton, 2014). The identified Lean principles have been numerically coded, and the CE practices have been assigned alphabetical codes for cross examination. The synergies within the literature were analysed individually and then overlayed to view the density of relationships. The synergies identified are shown within Table 6 to highlight commonalities, differences, and gaps within both topic areas as identified within the extant literature. Finally, the results of the matrix will be observed and discussed to understand the nature of said results and areas for future research to guide researchers and practitioners.

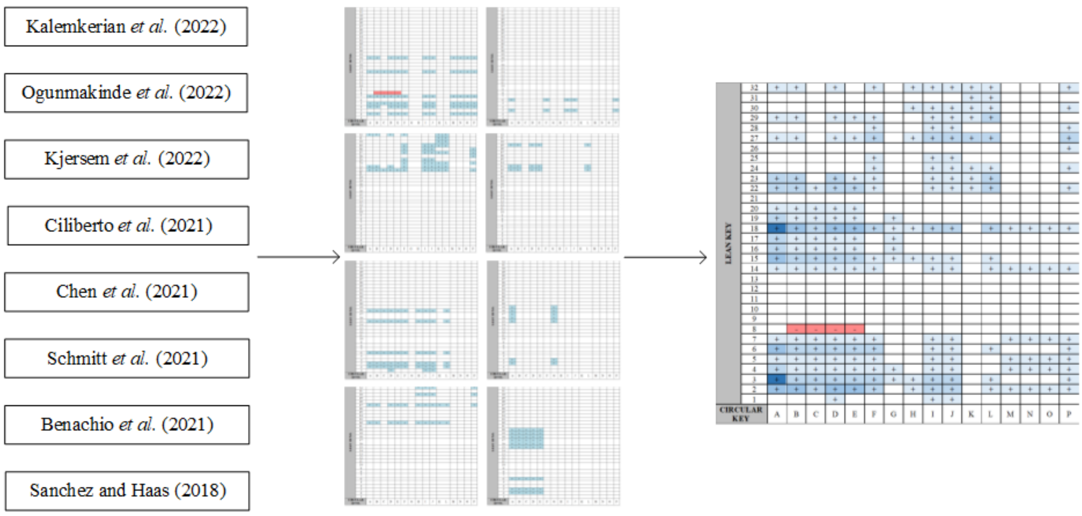

Figure 1: Development of qualitative research synthesis analysis matrix

THE LEAN PHILOSOPHY OF PRODUCTION

The TPS system established 14 management principles to improve the workplace and seven wastes (Table 1) which created the Lean philosophy of production (Liker, 2004). The Lean philosophy of production aims to promote value within the production process and reduce waste that hinders those efforts (Shah and Ward, 2003; Liker, 2004). The pull system utilised by Lean allows for the reduction of several wastes such as overproduction, waiting time, and inventory expenditure by drawing demand from the consumer (Liker, 2004). Lean principles create a consumer-led production with the “pull” system, whilst refining the process to ensure the quality of the product, and the effective management of the workers and their knowledge, well-being, and skills (Shah and Ward, 2003; Liker, 2004). Lean principles are made to be used together to form focussed multi-method strategies such as Just-In-Time (JIT), Total Quality Management (TQM), Human Resource Management (HRM), and Total Productive Maintenance (TPM) (Shah and Ward, 2003; Liker, 2004). The incorporation of the Lean philosophy within the production and construction industries has shown an improvement in the performance of the system in terms of cost, time, quality, and in turn the environmental impact of the process (Hines *et al.*, 2004; Liker, 2004; Marhani *et al.*, 2013; Carvajal-Arango *et al.*, 2019). Due to the positive impacts of Lean within production, it has become a popular philosophy within manufacturing and construction. Ultimately, it has become intertwined with modern methods of production management.

Table 1: Lean Principles from Liker (2004)

ID	MANAGEMENT PRINCIPLE
1	Base your management decisions on a long-term philosophy, even at the expense of short-term financial goals.
2	Create continuous process flow to bring problems to the surface.
3	Use “pull” systems to avoid overproduction.
4	Level out the workload (Work like the tortoise, not the hare.)
5	Build a culture of stopping to fix problems, to get quality right the first time.
6	Standardized tasks are the foundation for continuous improvement and employee empowerment.
7	Use visual control so no problems are hidden.
8	Use only reliable, thoroughly tested technology that serves your people and processes.
9	Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others.
10	Develop exceptional people and teams who follow your company’s philosophy.
11	Respect your extended network of partners and suppliers by challenging them and helping them improve.
12	Go and see for yourself to thoroughly understand the situation
13	Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly
14	Become a learning organization through relentless reflection (hansei) and continuous improvement
15	Over Production - Producing more than the customer demands
16	Inventory - Related to Overproduction, inventory beyond that needed
17	Transportation - The material be shipped directly from the vendor to the location in the assembly line
18	Waiting - Material is not being transported or processed
19	Over Processing - eworking, deburring, and extra work undertaken
20	Defects - Production defects and service errors waste resources i. Materials ii. Labour iii. Time vi. Reworking labour
21	Motion - This waste deals with ergonomics and health issues with respect to the workers and their job

LEAN CONSTRUCTION

The 11 Lean Construction (LC) principles were derived by Koskela (2002) (Table 2) to adjust for the differences within the construction industry’s lifecycle structure. The priciples of Lean construction utilise those of the Lean philosophy within a construction context to better suit the structure of the industry. It was identified within construction that there are activities that create process flow within the system preparing resources and conversion activities that transform resources into products of value (Alarcón, 1997; Koskela *et al.*, 2002). The flow and conversion activities within construction are a complex mix of materials, components, and discipline-specific labour (Alarcón, 1997; Babalola *et al.*, 2019). Thus, the application of the Lean philosophy is increasingly difficult as opposed to manufacturing due to the size and complexity of construction (Alarcón, 1997; Koskela *et al.*, 2002). Koskela’s (2002) LC principles focus on managing the complexity of the construction system in order to better apply Lean production principles (Alarcón, 1997; Koskela *et al.*, 2002). Communicating information, benchmarking, and evaluating activities are key in understanding the flow and conversion of resources to reduce the wastes identified by Lean (Koskela *et al.*, 2002). Furthermore, simplifying the process assists in the application of management strategies (Alarcón, 1997; Koskela *et al.*, 2002). LC aims to lower the complexity of the system with standardisation and simplification in order to reduce the waste caused by complex systems (Alarcón, 1997; Koskela *et al.*, 2002). Within construction the application of the Lean philosophy has shown similar promises of value as those found in manufacturing (Babalola *et al.*, 2019; Carvajal-Arango *et al.*, 2019). In summary, LC advances upon Lean production in an attempt to increase adoption within the vast and complex industrial system that is construction.

Table 2: Lean Construction Principles by Koskela *et al.* (2002)

KEY	LEAN CONSTRUCTION PRINCIPLE
22	Reduce the share of non-value-adding activities
23	Reduce the cycle time
24	Reduce variability
25	Simplify by minimizing the number of steps, parts, and linkages
26	Increase output flexibility
27	Increase process transparency
28	Increase value through the consideration of customer's requirements
29	Focus control on the complete process
30	Build continuous improvement into the process
31	Balance flow improvement with conversion improvement
32	Benchmark

THE CIRCULAR ECONOMY

The Circular Economy (CE) is a new structure for construction and production, becoming popular around the millennium (Govindan and Hasanagic, 2018). Now the CE is being proposed around the globe by organisations and governments as a solution to economic waste (McDowall *et al.*, 2017; Huang *et al.*, 2018). The CE is part of the most recent industrial revolution, Industry 5.0, the human-centric focus of industrial practice (MacArthur, 2013; Geisendorf and Pietrulla, 2018). The CE aims to reduce waste within the lifecycle of products by promoting value and reducing waste (Geisendorf and Pietrulla, 2018; Govindan and Hasanagic, 2018). This is achieved by creating a pull-system and closing the loop on linear waste removing value from the system (Geisendorf and Pietrulla, 2018; Govindan and Hasanagic, 2018). The CE has several principles in which to reduce waste and promote value within the lifecycle known as the 3Rs, 6Rs, or the 12Rs (MacArthur, 2013; Geisendorf and Pietrulla, 2018). The 3Rs are simply reduce, reuse, and recycle (MacArthur, 2013; Huang *et al.*, 2018). These outline the aims of the CE, to reduce the quantity of resources consumed, to reuse products and components, and finally, recycle waste back into the system to gain the maximum value from resources (MacArthur, 2013; Huang *et al.*, 2018). The 6Rs and 12Rs go further into detail, elaborating on the 3Rs with refuse, reduce, repair, reuse, repurpose, regenerate, rethink, remanufacture, recycle, recover, rot, and re-evaluate (MacArthur, 2013). Overall, the principles of the CE aim to consider the implications of the supply chain to avoid, manage, evaluate, and recover material waste within the supply chain.

Table 3: Circular Economic Principles

KEY	CE PRINCIPLE	DESCRIPTION
A	Reduce	The reduction of resources and waste at every stage possible. From design through to the end-of-life stage.
B	Reuse	The reuse of materials and components in new products or projects.
C	Remanufacture	The restoration of materials or components.
D	Recover	The collection of materials in their end-of-life period.
E	Recycle	The incorporation of recovered materials in new products.
F	Redesign	The reduction of waste and incorporation of recovered materials through product design.

CIRCULAR CONSTRUCTION

The CE within the construction industry is still relatively new, only appearing significantly within the literature since 2015 (Adams *et al.*, 2017; Benachio *et al.*, 2020). The construction industry has naturally developed a human-centric pull-system in some sectors as the requirements of the client are stated for the function of the project (Ghisellini *et al.*, 2016; Hart *et al.*, 2019). Though a higher level of consideration for the human element in the built environment is emerging in the fifth industrial revolution (Geisendorf and Pietrulla, 2018; Çimen, 2021). However, the manufacturing of materials and components for the construction industry still follows a linear mass production structure to supply projects (Hart *et al.*, 2019; Hossain *et al.*, 2020). Furthermore, the construction industry is one of the largest waste producing industries, making construction a target for CE innovation (Adams *et al.*, 2017; McDowall *et al.*, 2017; Benachio *et al.*, 2020). The practices used by the construction industry to implement closed-loop circular economic flows have been coalesced in Table 4. The practices utilized by the construction industry are focused on communication within the industry, simplification of the systems processes and components, and design according to the 3Rs. In totality, the CE within the construction industry collaborates, evaluates, and redesigns.

Table 4: Circular Economic Practices in Construction

KEY	CE PRACTICE	DESCRIPTION
G	Pull-system	Produce the number of products to the required demand to avoid materials and products requiring inventory space or being wasted.
H	Lifecycle Analysis	Evaluation of the activities and events in the lifespan of a given process or material.
I	Design for Maintenance	The consideration of maintenance within the design of the product to reduce depreciation of the value.
J	Design for Recovery	The consideration of resource and component recovery to reclaim value lost from the linear wasting of products.
K	Standardisation	The use of common designs, materials, or processes to reduce the amount of variation within the market. Overall, it simplifies the application of higher strategies.
L	Modularisation	The design of a product in sections to allow for the interchangeability of components/modules.
M	Supply-chain Management	The collaboration and management of members of the supply chain for better synchronisation of the project's supply.
N	Knowledge Management	The management of data and knowledge in regard to the project for a better understanding of the completed work and the proposed.
O	Stakeholder Management	The management of stakeholders for better communication and direction for the project's operational functionality.
P	Material Passports	The creation of passports for resources to communicate the resource's information and designed lifecycle strategy.

The initial practice for CE innovations is the analysis of the lifecycle to view the waste produced by industrial activities (Benachio *et al.*, 2020; Çimen, 2021). This evaluation is key to understand the problem within the system (Hossain *et al.*, 2020; Munaro *et al.*, 2020). Once identified, the waste can be considered within the design stage (Adams *et al.*, 2017; Benachio *et al.*, 2020). The waste can be designed out and reduced, designed for reuse, and designed for recovery (Adams *et al.*, 2017; Benachio *et al.*, 2020). Material passports are used to communicate the designed strategy for maintenance and recovery to enable its application (Hossain *et al.*, 2020; Munaro *et al.*, 2020). Designing for maintenance and recovery can be assisted by practices such as modularisation and standardisation of components to reduce complexity within the design (Adams *et al.*, 2017; Hossain *et al.*, 2020). These methods of production are also less wasteful as components are prefabricated in factory conditions (Hart *et* *al.*, 2019). Additionally, collaboration with the wider supply chain better enables the creation of a closed-loop CE structure within the industry (Govindan and Hasanagic, 2018; Çimen, 2021). SCM is therefore a core practice of the CE to design for and recover materials in the lifecycle (Govindan and Hasanagic, 2018; Munaro *et al.*, 2020). The management of stakeholders is also key to create a uniform direction for the design and application of the given strategy (Govindan and Hasanagic, 2018; Çimen, 2021). Altogether, the knowledge generated through the communication within the supply chain and stakeholders requires management and evaluation to further apply the 3Rs, 6Rs, or 12Rs (Munaro *et al.*, 2020). Ultimately, creating more value from the production and operation of the product.

CIRCU-LEAN SYNERGIES

The popularity of Lean and the CE in literature as solutions to unsustainable consumption naturally brought forth comparisons to determine their qualities. However, the topic is not yet saturated within the literature with only eight papers identified with both topics mentioned in the title, abstract, or keywords. Of the eight papers identified within the literature, four were based on manufacturing. Firstly, Ciliberto *et al.* (2021) conducted an initial study creating a series of matrixes comparing Lean and the CE finding strong correlations in the reduction of waste through evaluation and collaboration. Kjersem *et al.* (2022) found that Lean and the CE have many similarities within the process and production stages in terms of waste reduction and environmental/economic impacts. Schmitt *et al.* (2021) investigated the synergy with the aim of creating a three-level system for the strategies to be combined and incorporated into the product, process, and system levels of the economy. Schmitt *et al.* (2021) found that Lean compliments the process level of the CE strategy whilst the CE promotes long-term value. Kalemkerian *et al.* (2022) found similar results as Schmitt *et al.* (2021) in their investigation into Green Lean management which had limitations compared to the long-term environmental and economic gains of the CE. Overall, the initial investigations into the synergy between Lean and the CE are positive.

Within the construction industry the investigation of synergies between LC and the CE are fewer still. Several papers mention Lean and the CE though do not investigate or elaborate on the relationship. Sanchez and Haas (2018) suggested some initial benefits from the application of a CE with the Last-planner system. Sanchez and Haas (2018) proposed that Lean's last-planner pull-system and management strategies provided a beneficial structure for the application of a CE though did not specifically focus on investigating the relationship. Chen *et al.* (2021) found that the use of Lean can benefit the CE in the construction stage by mitigating the waste produced by activities and process. Furthermore, Ogunmakinde *et al.* (2022) hypothesised the use of modular prefabrication within LC can assist in developing CE methods within construction supply chains. Benachio *et al.* (2021) investigated the interactions between the two strategies within the construction lifecycle finding seventy-four positive and four negative interactions. Benachio *et al.* (2021) found the highest number of interactions surround off-site construction and prefabrication where Lean is better applied. Benachio *et al.* (2021) also investigated the interactions based on the stage in the construction lifecycle. Benachio *et al.* (2021) found that the construction stage has the highest number of interactions between the strategies. In summary, some synergies between Lean and the CE have been identified within the literature but only Benachio *et al.* (2021) conducted an investigation specifically into the synergy within the construction sector.

FINDINGS AND DISCUSSION

This research found that the synergies identified between Lean and the CE within the literature are positive overall but still in the early stages of investigation. The sample of literature identified for the study was minimal and largely focused on manufacturing and production over construction specific investigations of the synergy. The eight papers used within the matrix were analysed individually to understand the identify the synergies discussed within the literature, then coalesced in Table 5 for cross-examination.

Table 5: Synergies between Lean and the Circular Economy. Positive Interactions (Light Blue to Dark 1-4), Negative Interactions (Red).

LEAN KEY	32	+	+		+		+		+	+	+	+	+				+
	31											+	+				
	30								+	+	+	+	+				+
	29	+	+		+	+	+			+	+	+	+				
	28						+			+	+						+
	27	+	+		+	+	+		+	+	+	+	+				+
	26																+
	25						+			+	+						
	24						+			+	+	+	+				+
	23	+	+		+	+	+			+	+	+	+				
	22	+	+	+	+	+	+			+	+	+	+				+
	21																
	20	+	+	+	+	+											
	19	+	+	+	+	+		+									
	18	+	+	+	+	+	+	+	+	+	+		+	+	+	+	+
	17	+	+	+	+	+		+									
	16	+	+	+	+	+		+									
	15	+	+	+	+	+	+	+	+	+	+		+				
	14	+	+	+	+	+	+			+	+		+	+	+	+	+
	13																
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	8		-	-	-	-											
	7	+	+	+	+	+	+			+	+			+	+	+	+
	6	+	+	+	+	+	+			+	+		+				+
	5	+	+	+	+	+	+			+	+			+	+	+	+
	4	+	+	+	+	+	+	+		+	+			+	+	+	+
	3	+	+	+	+	+	+	+	+	+	+		+				+
	2	+	+	+	+	+	+		+	+	+		+	+	+	+	+
	1				+					+	+						
CE KEY		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P

The in the cross-examination of the literature on CE and Lean synergies, it was identified that the largest number of interactions were identified within the waste reduction principles and practices. This is supported by Benachio *et al.* (2021), who identified the most interactions between the two concepts which are within the manufacturing and construction stages. This further supports waste reduction as the core similarity between the topics. This further suggests that manufacturing and construction are perceived the most immediate stages in which waste can be reduced. In this effort, the pull system is utilised for the reduction of waste such as overproduction and inventory space in both strategies but was originally developed within Lean's philosophy (Liker, 2004). The human-centric pull-system of both strategies creates consumer-led value and was commonly identified as a similarity between the two strategies. The considerations present within both strategies for the consumers requirements assist in reducing waste caused by unwanted or unneeded products or elements. This is underpinned by another similarity between the two topics, the focus on long-term value and prioritisation of the big picture. By prioritising the long-term outcome, both strategies increase value, sometimes at the cost of short-term performance (Liker, 2004; Govindan and Hasanagic, 2018). In this regard, both strategies evaluate practice to improve the system. The Lean philosophy creates continuous improvement, benchmarking, and aims to increase transparency in order to identify and understand inefficiencies or wastes within the system for redesign. Similarly, the CE aims to analyse the impacts of the lifecycle with LCA to understand the material wastes produced and their impacts for redesign and reduction or strategic recovery of the waste. Overall, the reduction of waste is largely similar in terms of output though differs slightly in methodology.

There are also several differences between the two strategies. The distinct difference identified within the literature are the well-defined principles and wastes within the Lean philosophy that are more developed than the CE. The advantage of Lean's established practice enables granular waste reduction within the system's processes and activities whilst cultivating the workforce. The CE on the other hand is a more recent strategy that is still developing and therefore has not yet reached a level of maturity to specifically target wastes on a granular level. However, the CE also provides innovations to the Lean philosophy that can further increase waste reduction and value promotion within the system. The closed-loop structure of the CE strategy adds value from waste that cannot be designed out or reduced. The longitudinal nature of the CE strategy adds a system level consideration for value and waste which increases value retention over the lifecycle. The holistic closed-loop nature of the CE lifecycle compliments the Lean philosophy by elucidating on the long-term benefits of managing value and waste. Both points highlight deficiencies in which the other compliments. This suggests that not only are there significant similarities between the two strategies but complimentary difference in which the strategies support and develop one another. Furthermore, the Lean philosophy also aims to promote value from the workforce and their experience, knowledge, and skills. The management of human resources has shown to further increase value within the production and construction of products. In comparison to Lean, the CE has few practices for the enrichment of the human resources within the system. Additionally, Lean aims to educate and advance the workforce to better the overall organization and the extended supply chain. Thus, it is suggested that the use of Lean's human resource management could support the development of the CE's management philosophy. In summary, Lean's principles of collaboration between management and the workforce could help promote a culture of closed-loop recycling within management for construction and production and are not negative differences between the strategies. Overall, there are some differences between the strategies, though they are not necessarily negative and could be used to develop a new Circu-Lean philosophy for economic production. One study highlighted negative interactions between the CE and Lean strategies conducted by Ciliberto *et al.* (2021). Which identified the CE's innovative use of materials for new sources of value contradicted Lean's desire for thoroughly tested and simplified systems (Ciliberto *et al.*, 2021). There are no doubt further negative interactions between the two topics however there is no extant studies investigating this factor and therefore should be the focus of future studies.

The investigation into the literature for synergies between Lean and the CE found that there are many similarities and differences (Table 6). Primarily, a human-centric pull-system, the promotion of value, the reduction of waste, the simplification of processes, the long-term focus of the strategies, and evaluation for redesign. Through cross examination of the similarities within Table 6, areas in which the two strategies differ are highlighted by the lack of interactions between the strategies. Initially, the infancy of the CE management philosophy in contrast to Lean's, which has developed several management principles for the extraction and promotion of value from management and the workforce. Secondly, both strategies approach value promotion and waste reduction differently. Lean's reduction of process waste within flow and conversion activities provides a granular approach. Whereas the CE focuses on general material waste reduction and recovery through a holistic closed-loop approach. This suggests that where the strategies are lacking interactions within Table 6, said differences could be beneficial to the developing the opposing strategy.

CONCLUSION

In totality, the literature specifically on Lean and the CE in the construction industry is still within its early investigation of the synergy between the management strategies. Benachio *et al.* (2021) have conducted the most sophisticated study into the synergy and have identified multiple areas where positive interaction between the strategies exists. However, within the literature there is yet to be a publication of sufficient quality to support or contradict the study conducted Benachio *et al.* (2021). Furthermore, if the initial findings within the literature for production and construction are correct. The synergy between Lean and the CE could be extremely valuable for construction in the effort of meeting SDGs. Overall, the similarities between the strategies within the design and production/construction stages are vast and positive. Likewise, the differences, although stark, suggest a complimentary contrast if combined. Ultimately, providing guidance and structure for one another to innovate where the other is successful.

The novelty of this work is twofold, a review to coalesce and critique of the extant knowledge on the Circu-Lean synergy, and guidance for future research into the synergy between Lean and the CE. Future research would continue the investigation into the strategies' synergies within the construction industry to better understand the similarities and differences. Furthermore, the investigation into the similarities between waste reduction can provide an interesting platform for researchers to identify the best practice for waste reduction in the construction industry. Moreover, further research into the differences between the two strategies can elucidate on the shortfalls and areas in which the contrast between the two strategies can complement one another (E.g., HRM in the CE). The limitations of this study are largely due to the lack of construction specific research on the synergies between Lean and the CE. As the literature progresses the qualitative synergy within the matrix would become richer as the sample increases in size. Furthermore, at present there is little contradictory literature for the review of contrasting opinions within the research community

In summary, this research reviewed a newly founded body of knowledge on the synergies between Lean and the CE. The vast majority of interactions between the two strategies are positive and concentrated on waste reduction. And finally, it is suggested that the development of the literature surrounding the synergy between CE and Lean could converge into a Circu-Lean philosophy of economic production and construction.

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APPENDIX A: CIRCU-LEAN SYNERGISTIC CROSS-ANALYSIS

Analysis #1 – Interpretation of Ciliberto *et al.* (2021) analysis of the interactions between Lean and the CE in production

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Analysis #2 – Interpretation of Kjersem *et al.* (2022) investigation into Lean and the CE in the context of operations management

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Analysis #3 – Interpretation of Schmitt *et al.* (2021) analysis of Lean and the CE in a production context over multiple levels of the holistic system

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Analysis #4 – Interpretation of Kalemkerian *et al.* (2022) analysis of Green Lean and the CE in production

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Analysis #5 – Interpretation of Sanchez and Haas (2018) investigation into the planning for the CE

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Analysis #6 – Interpretation of Benachio *et al.* (2021) analysis of CE construction and LC

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Analysis #7 – Interpretation of Chen *et al.* (2021) literature review into the CE in the construction supply chain

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Analysis #8 – Interpretation of the synergies identified in Ogunmakinde *et al.* (2022) review of CE contributions to SDGs

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León William. & Guevara, Jose. (2023). "Semantic network analysis of lean construction literature." In: *Proc. 31st Annual Conference of the International Group for Lean Construction (IGLC31), Rybkowski, Z. K., Liu, M., and Sarhan, S. (eds)*, Lille, France, pp. 559–570. doi.org/10.24928/2023/0152. Available at: <https://iglc.net/Papers>

SEMANTIC NETWORK ANALYSIS OF LEAN CONSTRUCTION LITERATURE

León William[1] and Guevara Jose[2]

ABSTRACT

Lean Construction is a philosophy grounded in production theory that play a crucial role in promoting efficient, sustainable, and cost-effective practices across the Construction and Engineering Management (CEM) sector. To understand its impact, it is important to analyze the related concepts, synergies, information gaps, potential research paths, and new terms associated with such domain. Therefore, this research paper aims to develop a graphical and quantitative analysis of the LC literature using Semantic Network Analysis (SNA). The analysis builds a large network of interactions between concepts related to the implementation of the LC philosophy in construction projects, offering a novel perspective on reviewing the LC literature. It provides metrics and graphical tools to characterize, quantify, and interpret LC concepts such as Building Information Modelling (BIM), Integrated Project Delivery (IPD), Last Planner System (LPS), and Sustainable Construction, and enables the observation of emerging relationships with opposing concepts such as Earned Value Management (EVM) or information gaps related to Risk Assessment, Decision-Making, or Planning Reliability, which are equally crucial for the implementation of CEM. Overall, this study offers valuable contributions to the IGLC community by providing new perspectives on potential research routes and emerging concepts in the LC literature. It achieves this by synthesizing the relationships between LC ideas and concepts that are not traditionally connected to LC principles, such as Earned Value Management (EVM).

KEYWORDS

Lean construction, construction and engineering management, and semantic network analysis.

INTRODUCTION

Researchers in the field of Construction and Engineering Management (CEM) have developed useful methodological tools by leveraging quantitative and graphical analysis of bibliographic reviews (Herrera et al., 2020). While Lean Construction (LC) has been thoroughly studied over the past decades, there is a notable gap in the CEM domain when it comes to the integration of LC with other essential concepts in the construction industry (Heigermoser et al., 2019). Based on that, this study aims to address this gap by examining the relationships between LC studies and other relevant investigations focused on concepts, such as Building Information Modelling (BIM), Integrated Project Delivery (IPD), Earned Value Management (EVM), and sustainability.

In order to develop a quantitative and graphical synthesis of LC and its connection with other relevant concepts in the CEM domain, the study utilizes Semantic Network Analysis

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(SNA) (Salazar et al., 2021). This analytical tool allows for the development of networks between associated concepts in a literature review, making it possible to analyze LC and its synergies with other important ideas (Wen & Qiang, 2016). By characterizing, quantifying, and interpreting concepts that are commonly associated with LC and other terms with wide application in the construction sector, this analysis aims to provide a set of metrics and graphical tools that researchers can use to gain a deeper understanding of LC (Castelblanco et al., 2021). Thus, examining the integration of LC and CEM ideas.

POINTS OF DEPARTURE

LEAN CONSTRUCTION

Lean Construction is a philosophy grounded in production theory that play a crucial role in promoting efficient, sustainable, and cost-effective practices across the Construction and Engineering Management (CEM) sector (Koskela et al., 2002). The main focus of this philosophy is on improving the management and administration of construction projects by continuously improving processes, reducing waste, and increasing the final value of the construction product for the customer (Koskela et al., 2002). The adoption of this philosophy leads to higher productivity in processes, which in turn results in increased profitability of projects while minimizing the processes associated with the loss of value of the final product (Aslam et al., 2020). Hence, LC is considered a vital tool for optimizing resources and eliminating waste (Igwe et al., 2020).

SEMANTIC NETWORK ANALYSIS

SNA is a methodological approach for the analysis of dense networks between associated concepts, provides a quantitative, qualitative, and rigorous analysis of the existing synergies between concepts in literature (Motter et al., 2002; Pishdad-Bozorgi et al., 2017). Based on the development of networks of related words, this association analysis enables the extraction of metrics and the production of clear objectives and complex analyses related to the general structure of the relationships (Motter et al., 2002). The structure of this methodology involves creating a network of interconnected nodes from a set of words. If words are not associated with other nodes, this methodology reveals isolated connections or relations of interdependence between them (Herrera et al., 2020; Motter et al., 2002).

Using SNA allows for quantitative analyses of keywords from different articles and provides graphic and mathematical results (Zhai et al., 2014). Moreover, this technique enables the analysis of large databases with low computational requirements, making literature reviews more complex and comprehensive (Han et al., 2018). Therefore, this study employs SNA in evaluating and analyzing the LC and CEM literatures.

CONTENT ANALYSIS

Content analysis (CA) is a valuable technique that complements the SNA methodology. It involves a set of methodologies that allow researchers to extract information from a qualitative or quantitative interpretation of texts (Yearworth & White, 2013). By filtering, categorizing, and classifying information, researchers can carry out objective analyses that are suitable for graphic and mathematical analysis (Elo et al., 2014). In this study, the authors used content analysis to group themes, select fundamental concepts, evaluate trends, establish recurrences, and facilitate the SNA study of LC. In combination with SNA, content analysis enables a comprehensive and in-depth analysis of the literature on LC.

COMMUNITY ANALYSIS

Community analysis is a quantitative strategy used to understand and analyze the behavior of related concepts within a small group compared to the main network being studied (Newman, 2004). This tool helps researchers observe the grouping of sets of nodes that share similar characteristics. Community analysis is highly useful for characterizing underlying communities in large databases (Blondel et al., 2008). It also provides graphical complements that aid in understanding the overall network of nodes (Newman, 2004). By combining SNA, CA, and community analysis, this study analyzed LC and identified associated concepts and main networks from a rigorous selection of 500 research articles from bibliographical resources.

RESEARCH METHODOLOGY

The integration of SNA, CA, and community analysis in this study provides a synthetic view of the key concepts associated with LC. This methodology generates quantitative metrics that reveal significant relationships between LC and other concepts, while graphical representations visually demonstrate the density of these connections. The approach comprises six steps, as presented in Figures 1 and 2, and discussed below.

First Step – Paper Selection Strategy

This stage involved the search for relevant articles on the Web of Science database. From the selected articles, a set of core concepts were extracted to establish the scope of the SNA network and to guide the search patterns used in the Web of Science and Scopus search engines (Doerfel & Barnett, 1999). This search yielded approximately 1,800 records. For the first search cycle only the term Lean Construction was used. After finding a first group of high-recurrence keywords, the search was supplemented with a second cycle that included keywords as Building Information Modelling, Last Planner System, Integrated Project Delivery, and Sustainability.

Second Step – Paper Filtering and Categorization

After obtaining an initial total of 1,800 records in the Web of Science database, only the highest quartiles (1, 2) and records related to CEM were selected, resulting in a final set of 500 articles based on citation rates (de Castro e Silva Neto et al., 2016). The objective of this selection was to define the scope of the research and obtain a set of highly relevant articles for the SNA study. Moreover, this set of 500 articles was classified based on their type and central theme to identify research trends and recurrent thematic nuclei in academic research (Castelblanco et al., 2021). This exercise enabled the observation of the most recurrent themes in LC academic research, with the involvement of peer reviewers.

Third Step – Keywords Selection

This phase focused on extracting keywords from the 500 research articles (Bao et al., 2018). Titles, abstracts, and introductions of each article were analyzed, along with keywords suggested by the author, journal, and database. The extracted keywords were then filtered based on their significance and recurrence within the article. A maximum of 10 keywords were selected from each article to enhance SNA analysis by concentrating computational efforts on the most relevant and representative words (Eteifa & El-adaway, 2018). A standardization process was carried out to eliminate keyword redundancies, leading to a final set of 975 keywords across all 500 articles. This standardized approach improved the interpretation of the research articles by highlighting their core ideas, communicative intent, and content, and provided greater clarity for the subsequent SNA and CA analyses.

Fourth Step – Matrix Development

This step involved a quantitative analysis to determine the recurrence ratio of each keyword in the 500 articles. A matrix was constructed with 975 rows and 500 columns, where each row represented a keyword and each column represented an article (Castelblanco et al., 2021). A value of 0 was assigned to the intersection of a keyword and article if the word was absent from the article and 1 if it was present. Subsequently, the transposed matrix was created, with the number of articles in the rows and the total number of keywords in the columns (Hanneman & Riddle, 2005). This matrix allowed for the identification of the recurrence relationship between pairs of words. Finally, the multiplication of the keyword adjacency matrix and its transposed matrix was carried out to complete the process. This methodology enabled the identification of the most important and recurring keywords in the literature related to Lean Construction (LC) and their relationships with other concepts.

FIFTH STEP – NETWORK DEVELOPMENT

A general network was built, and it was possible to observe the geometric configuration of concepts, density of the network, key concepts, and the periphery of the network. This graphical analysis can show isolated or less relevant concepts. A specific network was built for specific subgroups (sub-communities) with high relevance in the main network.

SIXTH STEP – SNA METRICS AND VALIDATION

The collected data was analyzed for coherence and consistency, and validated using UCINET, Gephi, and Microsoft Excel software. It is important to acknowledge that the methodological categorization of keywords can be subjective, leading to limitations in generalizing the state of the art in LC (Bao et al., 2018). However, this article followed a rigorous validation process, including peer review to filter keywords, and verification of connection nodes across different software platforms.

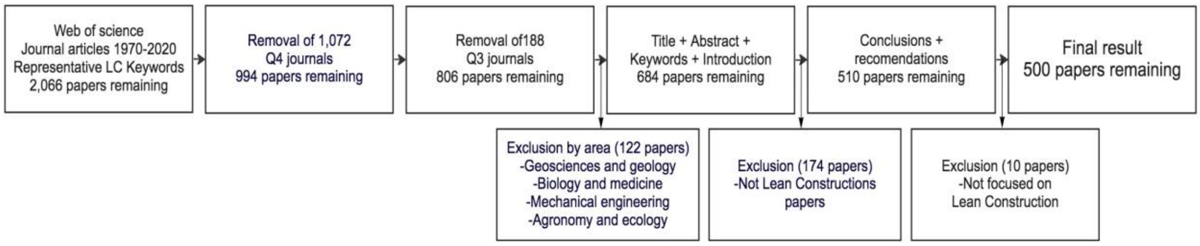

Figure 1: Paper filtering and categorization

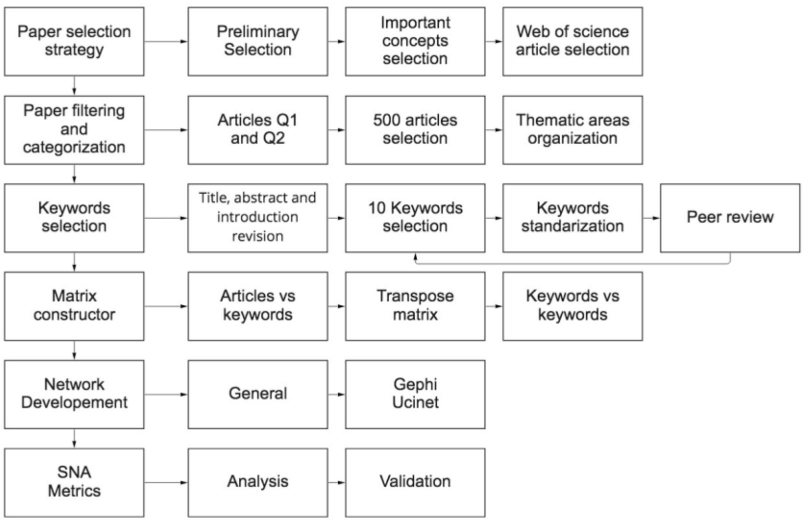

Figure 2: Methodology

RESULTS

The methodology stage yielded a set of networks (1 general structure and 5 sub-structures) that reflect the overall behavior of the LC-related literature and its primary relationships with recurring keywords within the CEM domain. It is noteworthy that the primary outcome is the creation of a semantic network between the 975 filtered keywords and a specific analysis of the sub-communities identified in the modularity coefficient analysis. To fully comprehend the significance of the centrality and cohesion metrics acquired in this study, several concepts have been defined in Table 1, as shown below.

Table 1: SNA Metrics

SNA metric	Meaning
Density	The number of co-occurrences between all keyword pairs as a percentage of the total number of coexistences between all keywords is referred to as density. (Hanneman & Riddle, 2005).
Clustering Coefficient	Metric used to quantify how closely related concepts are to one another. It is higher when particular thematic groups show strong internal interconnection (Freeman et al., 1991).
Modularity	The density of links within communities as opposed to links between communities is measured by a scalar value between -1 and 1, which is known as modularity. (Blondel et al., 2008).
Number of Connections	The quantity of connections between nodes serves as a measure of connectivity and the significance of each individual node inside a network. (Eteifa & El-adaway, 2018).

GENERAL NETWORK

Table 2 summarizes the cohesion metrics found in the semantic network of LC. The general network consists of 975 nodes and is formed by several sub-communities. These communities share common characteristics and are grouped based on color patterns to facilitate separate study. The analysis of communities provides valuable insights to researchers into the interrelationships between different concepts across the field of LC.

The network presented in Figure 3 shows the principal concepts observed in the center of the graph and less important concepts observed in the periphery. A summary of the nodes with the greatest impact is shown in Table 3, along with some of the most relevant centrality measures for this study.

PROJECT MANAGEMENT AND ORGANIZATIONAL CULTURE

The first sub-community identified on the main network is Project Management, as shown in Figure 4. This network comprises a high number of nodes, representing approximately 28.7% of the total network. The next community identified within the main network is Organizational Culture, which is the largest community, accounting for 36.5% of the nodes, as shown in Figure 5. Table 3 group the main nodes, which exhibit high level of density for both structures.

PRODUCTION PROCESS AND MODEL ANALYSIS

Production Process is the smallest community in the whole network. It includes 10 nodes and 17 relationships, comprising around 1% of the main network, as shown in Figure 6. On the other hand, Model Analysis entails roughly 8% of all keywords with 75 nodes and 149 connections. It shows few relationships per node despite exhibiting strong modularity indicators, low density, and high fragmentation as shown in Figure 7.

CONSTRUCTION PROCESS

This community is a medium-sized network with 77 nodes and 139 relationships. Metrics indicate high modularity and low density, with nodes exhibiting few relationships, as compared with other communities. Furthermore, this community also presents a small number of relationships, as shown in Figure 8, but it still represents a sizable portion of the total nodes, comprising about 8% of them.

Table 2: Network-based Measures

		Nodes	Number of Connections	Density	Clustering Coefficient	Modularity
	General Network	975	11852	0.025	0.774	0.226
Sub-Community	Project Management	280	4137	0.106	0.749	0.148
	Organizational Culture	356	1218	0.019	0.742	0.708
	Model Analysis	75	149	0.054	0.901	0.91
	Construction Process	77	139	0.048	0.867	0.931
	Production Process	10	17	0.378	0.75	0.612

Table 3: Node-based Measures

General Network					
ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A454	Lean Construction	1678	0.008	0.302	0.102
A337	Green building	911	0.006	0.296	0.071
A52	BIM	880	0.001	0.015	0.001
A145	Construction Industry	870	0.009	0.179	0.031
A405	IPD	789	0.009	0.245	0.015
Project Management (Sub-Community 1)					
ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A454	Lean Construction	1185	0.599	0.252	0.112
A52	BIM	648	0.473	0.226	0.052
A337	Green Building	636	0.032	0.017	0.001
A145	Construction Industry	621	0.444	0.229	0.033
A405	IPD	563	0.419	0.223	0.025
Organizational Culture (Sub-Community 2)					
ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A966	Workflow	47	0.115	0.559	0.195
A267	Earn Value Method	39	0.085	0.260	0.101
A461	Lean Production	38	0.090	0.490	0.085
A154	Construction Planning	24	0.065	0.296	0.053
A567	Organizational Culture	23	0.068	0.304	0.077
Production Process (Sub-Community 3)					
ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A489	Machine learning	2	0.333	0.458	0.183
A529	Mining industry	2	0.333	0.199	0.211
A933	Variation In Production	2	0.222	0.410	0.067
A951	Waste In Construction	2	0.222	0.381	0.071
A974	Worker Change	2	0.222	0.109	0.066
Model Analysis (Sub-Community 4)					

ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A120	Computation Modelling	4	0.068	0.351	0.141
A548	Multiple Regression Model	4	0.068	0.203	0.239
A870	Task Duration	4	0.068	0.386	0.063
A889	Time Buffer	4	0.068	0.471	0.077
A553	Nonlinear Dynamic Analysis	4	0.068	0.212	0.021
Construction Process (Sub-Community 5)					
ID	Keyword	Number of Connections	Degree Centrality	Eigenvector Centrality	Betweenness Centrality
A170	Construction system	5	0.079	0.782	0.311
A146	Construction innovation	3	0.053	0.010	0.083
A406	Integrated Project Team	3	0.053	0.010	0.105
A471	Line of balance	3	0.053	0.619	0.191
A609	Policymaking	3	0.053	0.001	0.049

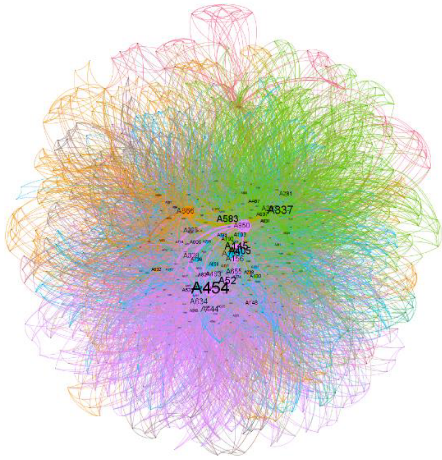

Figure 3: General Network

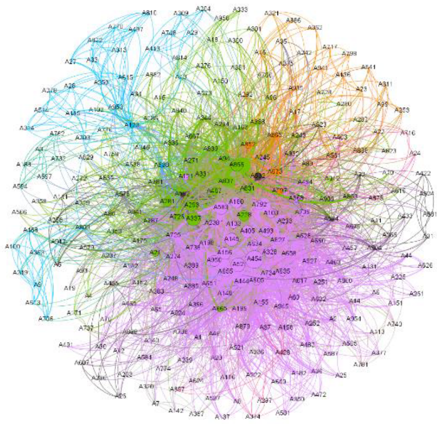

Figure 4: Project Management

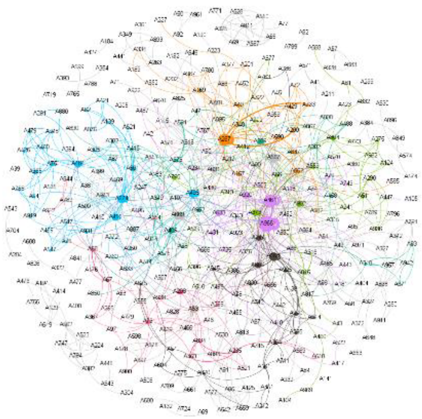

Figure 5: Organizational Culture

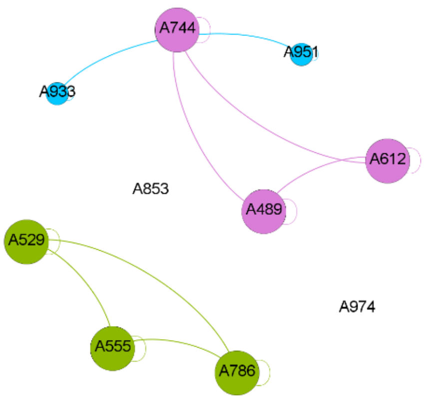

Figure 6: Production Process

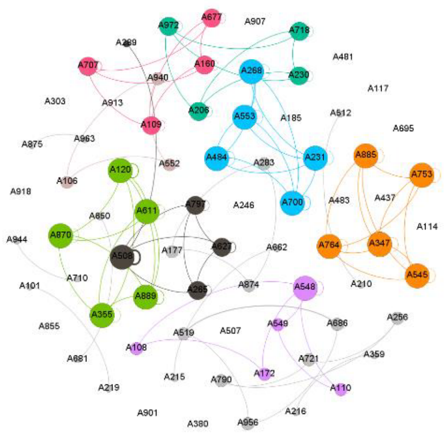

Figure 7: Model Analysis

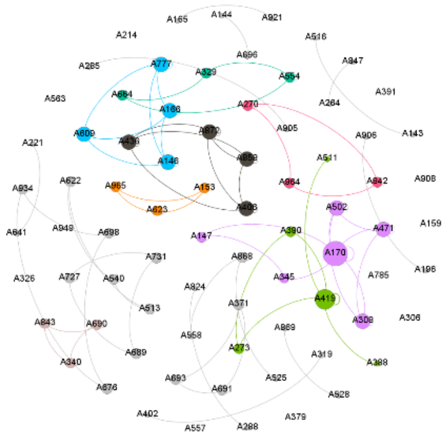

Figure 8: Construction Process

DISCUSSION

The review of literature derived from the SNA model yielded important results regarding the current state of art of Lean Construction (LC). The analysis shed light on concepts of greater proximity, the intensity of the interrelationships, and most importantly, the existing knowledge gaps between LC and some of the most recurring concepts aimed at optimizing and improving processes in the CEM domain.

Firstly, as expected, LC is the term with the highest recurrence in the main network. Concepts such as the Last Planner System (Ballard, 2000), Integrated Project Delivery (Eckblad, 2007), and Building Information Modelling (Sacks et al., 2010) are the closest concepts to LC in current literature, which aligns with Lean principles (Power & Taylor, 2019). In contrast, concepts such as Target Value (Gomez & Rameson, 2019), Flow Value, and choosing by advantages (Schöttle et al., 2019) are concepts that not appear because they are within the principles of LC and are a type of redundance inside the SNA model.

Secondly, the network analysis mathematically confirms the existing relationship between LC, Integrated Project Delivery, Last Planner System, and Building Information Modelling, but it also identifies new terms that are not conventionally associated with LC. Particularly, the emergence of Green Building (Pasquire & Ebbs, 2017; Sarhan et al., 2018) within the five most important nodes around LC is an interesting discovery. While LC is commonly associated with value generation, waste reduction, or continuous improvement (Landim et al., 2022), its association with sustainable development and environmental responsibility concepts is relatively novel. This reveals a new avenue of research that delves into understanding the synergy between LC and the implementation of sustainable projects (Sarhan et al., 2018). Recent construction projects have shown a trend towards coordinated implementation of LC principles and environmental impact mitigation strategies, which is compatible with the findings in this research article (Francis & Thomas, 2019). Furthermore, terms such as Green Building (Ruiz & Guevara, 2021) are shown to be more prominent than terms such as Project Performance, Productivity, or Process Optimization. This highlights the dynamic nature of LC and its ability to adapt to the new requirements and needs of the environment.

Thirdly, while the network analysis confirms the quantitative relationship of LC with traditional and new concepts, it also highlights gaps in literature regarding LC philosophy. Issues such as risk assessment and mitigation (Andenaes et al., 2019) are not extensively documented in relation to LC, and concepts such as Planning reliability or Decision-Making (Abdel-Jaber et al., 2022) are not explicitly linked to LC, but are undoubtedly critical to the structuring and execution of construction projects. Similarly, the lack of connection between LC and quality or innovation indicates gaps in knowledge and presents opportunities for new lines of research aimed at continuing to refine, understand and implement LC. In this way, the proposed SNA methodology enabled the verification of relationships, identification of new synergies, and characterization of knowledge gaps.

In addition, it is important to mention that despite the existing relationship between EVM and LC, EVM has been characterized as not being fully compatible with LC implementation (Kim & Ballard, 2010). However, the relationship between these two concepts exists and is strong due to recurring research that criticizes, compares, and/or combines EVM with LC principles (Cândido et al., 2014). Accordingly, this study not only finds LC linkages with compatible concepts that present synergy and complement each other but also finds terms or concepts that, despite seemingly going against LC postulates, are necessary to explain and deepen the existing knowledge. This also denotes that researchers around the world are examining the possibility of combining EVM with Lean, which is a preliminary indication of how construction projects are being developed worldwide (Cândido et al., 2014).

Finally, the results highlight the importance of variability in the execution of construction projects and their relationship with LC. For example, the process-oriented philosophy of LC, which emphasizes continuous improvement, is closely linked to reducing variability in processes, durations, and methods (Fischer et al., 2021). Therefore, investigating the relationship between LC implementation and variability reduction through performance metrics and indicators could provide valuable insights for future research.

IMPLICATIONS

The current research has practical implications for academics and practitioners in the CEM domain, as the employed methodology improves transparency and highlights semantic connections in a synthetic manner. As demonstrated in Table 3 and Figures 3-8, this study establishes links between LC keywords and critical CEM concepts. This is particularly relevant for those who are not familiar with the LC philosophy.

Results show that Machine Learning has emerged as a powerful tool in LC research (Pasquire & Ebbs, 2017). Technological innovations and computational developments have opened up new avenues for research that complement traditional methods and have provided new opportunities to study and deepen LC principles through modelling or numerical analysis tools. This development suggests that LC is increasingly being analyzed through data-based reasoning, a trend that is likely to gain more popularity in the years to come.

Furthermore, this study highlights the close association between non-linearity and complexity in the context of construction, which is a significant knowledge gap in LC literature (Murguia & Urbina, 2018). This gap indicates the need for future research to explore the complexity of construction projects, their uncertainty, and dynamics in greater detail through emphasizing LC ideas. It is found that LC has a determinant impact on the construction industry, as other economic sectors such as the mining industry have been interested in adopting LC philosophies for the execution of their processes (Castillo et al., 2015).

The analysis also reveals that the term "construction system" is commonly used in LC literature, implying that future research can focus on a systemic view of construction processes (Vásquez-Hernández et al., 2022). This view emphasizes construction as a large system with elements that are interconnected, interdependent, and constantly evolving.

CONCLUSION

The literature review presented in this study provided a visual and quantitative analysis of the linkages between LC and CEM concepts. The study reveals significant knowledge gaps that are linked to the interior of construction projects but are absent in their relationship with LC. These findings have the potential to reveal a new landscape for LC research, with knowledge gaps that are likely to continue existing due to the evolution of LC.

The proposed literature review highlights the significance of LC in the CEM domain and the close synergies it shares with essential concepts such as IPD, LPS, BIM, and Green Building. The SNA offered the authors the opportunity to visualize the nodes associated with LC and the communities underlying this large network. The study reveals approximately 975 keywords grouped in a network with high values of clustering coefficient, density, and modularity.

The fragmentation of nodes in smaller communities with similar characteristics suggests that concepts associated with LC exhibit modular behaviors. This indicates that there are groups of nodes that tend to be more related to specific groups of keywords, making it difficult for a node to connect with other communities. However, terms such as LC, LPS, IPD, and Green Building tend to have low modularity and are often related to more than one community. This implies that most communities have low density values because they are not significantly related to each other.

The also study shows that there are critical gaps in academic research related to LC and concepts such as Risk Assessment, Decision Making, Artificial Intelligence, Planning Reliability, and Innovation in Technology. This finding highlights the importance of utilizing graphical and quantitative tools to identify current relationships, discover new links, and identify information gaps to further advance researchers' understanding and application of LC in the construction industry.

Overall, this study offers valuable contributions to the IGLC community by providing new perspectives on potential research routes and emerging concepts in the LC literature. It achieves this by characterizing the relationships between LC ideas and concepts that are not traditionally connected to LC principles, such as Earned Value Management (EVM).

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UNTANGLING THE CONCEPTS OF VALUE AND VALUES

Frode Drevland[1] and Jardar Lohne[2]

ABSTRACT

The concept of value is widely used in lean construction (LC) literature, but researchers and practitioners lack a common understanding of the term. This is partially due to confusion between value (singular) and values (plural), which are two different concepts. This paper aims to provide a clear and concise understanding of the two concepts of value and values, separating them from each other and explaining their relationship. Furthermore, the paper discusses and exemplifies what these two concepts themselves entail. In doing so, the paper also introduces new terminology relevant for understanding and describing value and values in construction projects. Finally, the paper concludes that value and values research should be more precise in terminology than current literature.

KEYWORDS

Value, values, lean construction

INTRODUCTION

Value is a fundamental concept within lean construction (LC) and is one of the most commonly used terms in all LC-related literature. For example, the word value appears in the title or abstract of nearly a third of all IGLC papers (*IGLC.Net*, n.d.)

In 2010, Salvatierra-Garrido et al. (2010) critically reviewed the concept of value in LC theory, concluding that neither researchers nor practitioners had reached a common understanding. Since then, several authors have tried to lock down the concept of value (Drevland & Lohne, 2015; Drevland & Svalestuen, 2013; Khalife & Hamzeh, 2019). However, the concept of value is still very much fuzzy in the LC community.

Contributing to this fuzziness of value is the concept of values. While one could intuitively believe that values are not the plural of value, this is not so. Instead, they are entirely different – albeit related – concepts. As we will expand upon later in the paper, value (singular) is the specific result of an evaluative judgment of an object; values (plural) are general and fundamental beliefs about what is right and important in life.

Values and value are often confounded (Sánchez-Fernández & Iniesta-Bonillo, 2007). In the LC community, Some authors have covered the difference between the concepts (e.g., Drevland & Lohne, 2015; Khalife & Hamzeh, 2019; Schöttle et al., 2020). However, our impression from the recent IGLC conference is that value and values are still often confused. Moreover, both concepts on their own still seem very fuzzy within the LC community.

We would argue that one issue with previous LC authors' coverage of values as a concept is that it has been superficial – sufficient to broadly distinguish the term from value but not sufficiently for the reader to understand the concepts of values in depth.

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The purpose of this conceptual paper is to untangle the concept of values and values, and to make them easier understandable. That is, we seek not only to separate the concepts from each other but also from themselves. As shown later in the paper, both concepts have different definitions in the literature.

However, while the paper, to some extent, considers differing definitions of these concepts, we do not present a literature review of the topic. Instead, the aim is to create a to-the-point understanding of the concepts relying on a few select sources. We seek to pierce the veil of fuzziness that seems to surround both concepts of value and values, and make them understandable to the LC community members.

The paper starts by tackling the concept of values – explaining how values are beliefs about what is important in life and how one should behave. After that, the paper moves on to value, explaining how value results from an evaluative judgment and considers what elements play a role in this judgment, including how values play an essential role. Finally, the paper argues and concludes that research relating to the concepts of value and value should be a lot more stringent concerning terminology than what can be observed in the current LC body of literature.

VALUES

In the introduction, we wrote that there is a difference between values (plural) and value (singular). This statement is a truth with modifications. Values (plural) have to be the plural of something. In the seminal work, "The Nature of Human Values", Rokeach (1973) distinguishes between an object having value and a person having *a* value. However, people never have only one value; instead, they have several organised in *value systems*. Therefore, human values are seldom referred to in the singular. To avoid confusion, this paper explicitly uses the term human value when referring to such values in the singular.

Different authors have presented different definitions of values (Hofstede, 1985; Rokeach, 1973; Schwartz & Bilsky, 1987). However, the difference lies mainly in the wording. Most definitions of values found are conceptually the same (Schwartz & Bilsky, 1987). This paper mainly adopts Rokeach's (1973) conceptual framework, finding it superior to others regarding understanding the difference and relationship between value and values.

The literature commonly agrees that values are concepts or beliefs of what is important in life (Hofstede, 1985; Rokeach, 1973; Schwartz & Bilsky, 1987). Furthermore, what is important in life encompasses both the end states one seeks in life and how one should behave. In other words, there exist both ends-values and means-values.

Rokeach (1973) explicitly distinguishes between terminal and instrumental values. Terminal values are the end-states one seeks to achieve. Rokeach places them broadly into two categories. The first is social values. That is, the end states one seeks to achieve at the societal level – for example, "world peace" and "equality". The second category is personal values – for example, "a comfortable life" and "happiness". As for Rokeach's instrumental values, they are values that guide behaviour. Examples of these are "honest", "responsible", and "polite".

Human values are more or less constant over one's lifetime and are primarily learned in childhood (Rokeach, 1973). Initially, values are taught and learned individually, without considering their relation to other values, in a definitive and absolute way. However, once one matures, one will increasingly face situations where these values can conflict. For example, if you observe a friend doing something bad and you are asked to tell what happened, should you be loyal to your friend and lie, or should you be honest and tell the truth? Once a value is acquired, it becomes part of a structured system of values where each value is ranked in relation to the others based on its priority – a *value system*.

This value system organises one's values hierarchically (Rokeach, 1973). For example, two fundamental human values are self-preservation and protecting others. Say you find yourself in a burning building. You have two alternatives, evacuate yourself immediately or help others escape. The value you assign to each option depends on how you rank the abovementioned values.

A person typically has a relatively small number of values (Rokeach, 1973). While different individuals and cultures will have different hierarchies in their value systems, most human values are shared across the globe (Rokeach, 1973; Schwartz, 2017; Schwartz & Bilsky, 1987). Several authors have developed standardised frameworks for these values – for example, Rokeach's (1973) Value Survey or Schwartz's Theory of Basic Values (Schwartz, 2012).

While Schwartz's Theory of Basic Values is more widely acknowledged and used in modern times, the level of abstraction is also higher. That is, Schwartz employs higher-level concepts, such as *hedonism* and *achievement,* compared to Rokeach's more straightforward ones, such as *happiness* and *social recognition*. Therefore, for pedagogical purposes, the example values we use in this paper are primarily based on Rokeach's Value Survey as they are more concrete – and thus more relatable.

Organisational values

In this section, we have so far discussed human values, which relate to individual people. However, in construction projects, we seldom deal with individuals. Even with single-family homes, there will be several family members, each with their values. Related to human values, there exists the concept of *organisational values*.

According to (Liedtka, 1991), organisational values "take the form of guiding principles and beliefs perceived to exist by organisational members as a whole" – in other words, they are essentially the same as human values, but for organisations. However, organisational values are not as straightforward as the statement by Liedtka suggests. For example, according to Zhang et al. (2008), corporate values are often formulated by those in leadership positions, leading to a gap between the values of the organisation and its employees.

It is beyond the scope of this paper to explore the topic of organisational values thoroughly. However, related to understanding the concept of values, we believe it essential to understand that organisations have values like individuals. Furthermore, we would like to point out that similar to the frameworks categorising human values, frameworks exist for mapping values at the organisational level, for example, the Competing Values Framework (Cameron & Quinn, 2011).

VALUE

Back to the disambiguation made at the start of the previous section, value (singular) relates to an object having value. Therefore, properly understanding value as a concept entails understanding how the value of an object is determined. However, before dwelling on this matter, we must point out that value (singular) is not a singular concept.

As with values, there are many different definitions of value in the literature across various fields (Drevland et al., 2018). Most of them are variants of value being the relationship between what you get and what you give – or cost/sacrifice and benefit. However, different value concepts still exist within this notion of value. For example, market value – a term from economics – is the price one has to pay to acquire a good or service on the open market. With this value concept, value is objective and measurable. Thus, this value is very distinct from value as a concept within lean.

The lean concept of value concerns customer value (Drevland et al., 2018). Since, within the lean philosophy, all project stakeholders are considered project customers, this equates to stakeholder value. There are many stakeholders in a construction project, all of whom will have different notions of what is valuable (Drevland & Tillmann, 2018). Value for one stakeholder will not be value for another stakeholder. In other words, value is subjective or particular for a given stakeholder and cannot be objectively measured (Drevland et al., 2018). Indeed, value in our context is the result of an evaluative judgment.

While evaluative judgment is another term with various definitions across fields, we here use it as commonly used in the fields of psychology and neuroscience. There, evaluative judgment is a fundamental aspect of human cognition that allows individuals to assess the degree of liking or disliking towards a stimulus (Clemente et al., 2021). This evaluation process helps people compare and choose alternatives, make decisions and prioritise actions.

When making evaluative judgements, people draw on various processes and sources of information. (Musch & Klauer, 2003). In the following, we will expand upon how the value of an object is determined through an evaluative judgment. This explanation is anchored in and built upon our previous research. In Drevland et al. (2018), we defined value on a fundamental level by developing nine tenets on the nature of value. Together, these tenets yield a more comprehensive definition of value than found elsewhere. For discussion of how our definition of value differs and compares to other definitions found in the lean construction literature and other fields of research, we defer to Drevland et al. (2018).

In Drevland et al. (2018), we included a rather lengthy definition of value that incorporates all nine tenets. The explanation and discussion of value in this section include all elements of this definition and the tenets; however, we will here use a cut-down and modified version of the definition for pedagogical purposes.:

> *Value is the result of an evaluative judgment of the relationship between what someone gets from an object and what they must give to obtain and use it.*

Figure 1 illustrates the above definition and shows three main elements of value: 1) the value object, 2) the value subject – for whom is the value, 3) and the evaluative judgement itself.

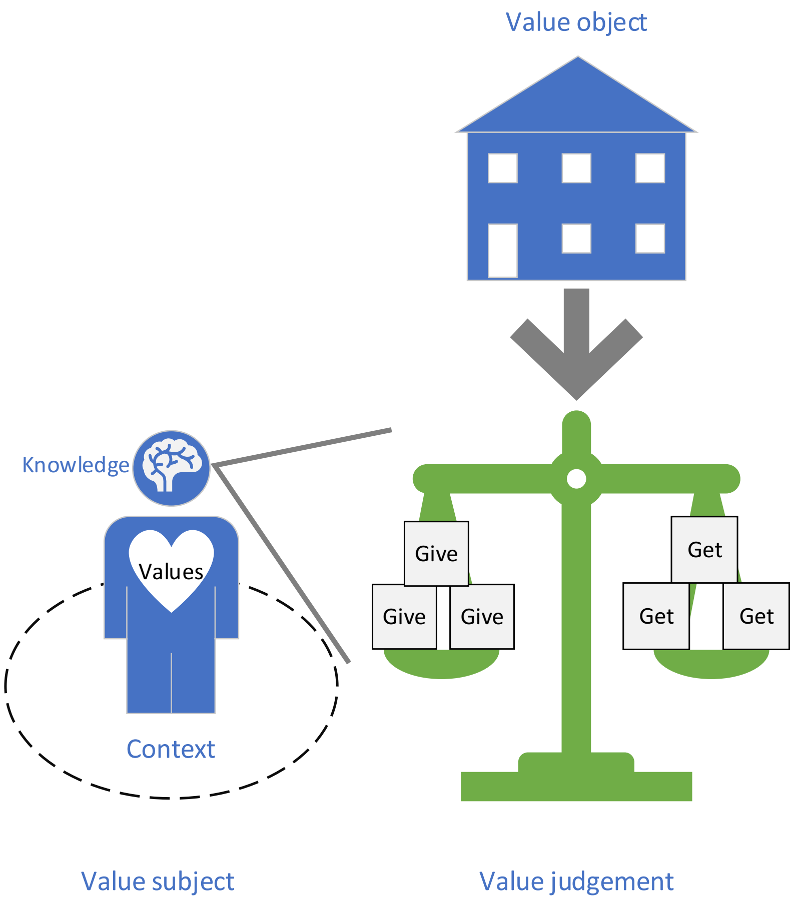

Figure 1: Graphical Definition of Value

THE VALUE OBJECT

We will here introduce the term *value object* to denote the object that is the target of an evaluative judgment to determine its value. The value object can be a physical object – like a building – or an immaterial product or a service. It matters not; what matters is what about a value object, in general, we consider when making a value judgment. In our context, the value object is the project – encompassing both the final built facility and the design and construction process delivering it.

Value is the relationship between what one gets and gives; thus, when making an evaluative judgment, one considers what one must give or sacrifice to obtain – and possibly operate – the object and what doing so will provide one with.

One may consider a host of different factors when judging a value object. Authors have used differing terms for these underlying factors. For example, Drevland et al. (2018) refer to them as get-and-give factors, while (Kliniotou, 2004) calls them value drivers. In this paper, we will refer to them as value factors. We will revisit value factors later in the section. However, before doing so, we must first cover some central aspects of the value judgment and how the characteristics of the value subject play into this judgment.

THE VALUE SUBJECT

Value being subjective entails the value of an object is always for someone. We will here introduce the term *value* subject to refer to this someone. When a value subject judges the value of an object, three attributes of the value subject matter (Drevland et al., 2018): Their knowledge, values and context – or metaphorical speaking, their heel, heart, and their head.

Heel – What context are one's feet planted in

What someone considers valuable depends on where they – metaphorically speaking – stand, that is, the context in which they find themselves. For example, someone living in a country with high-quality tap water will typically not see much value in bottled water. However, if they were to find themselves in the desert dying of thirst, they would judge the same bottle of water very differently.

Context encompasses the value subject's current needs and goals. Drevland (2021) relates an example from hospital projects in the Mission District of San Francisco, where a demographic shift in the neighbourhood caused the client to want to provide different services at the hospital and thus needed other physical infrastructure. In other words, what they saw as valuable changed because their context changed.

Hearth – One's values: what one cares about

As previously explained, values are general beliefs of what is important in life. An example of such a human value would be "protecting the environment". Someone who cares about the environment will always prefer "greener" products and assign a higher value to a green building, everything else being equal. However, everything else is seldom equal. Making a greener building could also make it more expensive. For an individual buying a home, the human value of "protecting the environment" could potentially come into conflict with values such as "having a comfortable life" and "taking care of one's family". Whether they prefer a cheaper non-green home or a more expensive green home would then depend on their value systems and how their values rank internally. Thus, the value judgment is highly dependent on the values of the value subject.

Head – What one knows

When people judge an object's value, they depend on the knowledge they possess (Drevland et al., 2018). Knowledge not only about the value object but also its context, alternatives, etc. The knowledge that someone has can very well be flawed or lacking, leading to an erroneous perception of what value is. For example, recent history is fraught with cases of sustainable initiatives initially considered valuable that – in hindsight – have turned out not to be sustainable and of little value, such as biofuel (Antwi-Bediako et al., 2019).

In addition to the perceived value – the value someone perceives given the knowledge they possess – Drevland et al. (2018) introduces the term *true value* to represent an ideal notion of the value that would be perceived had the value judge had perfect knowledge.

While the concept of true value is purely abstract and theoretical – we can never know the true value of an object – it is helpful in our context. In some fields, the perceived value is all that matters Drevland et al. (2018). For example, marketing is only concerned with the value the customer perceives when making the buy/no buy decision. In construction projects – especially with newer value-centric project models – the goal is to maximise the value for the customer at project delivery, not just deliver what they perceived as valuable at the beginning. In other words, although we do not know the true value for a project stakeholder, we strive to achieve it.

When the value subject and the value judge are not the same

The head, hearth and heel metaphor above assumes that the value judge and the subject are the same entity; however, this is not necessarily the case. The value judge may not be the same individual as the value subject. For example, a designer makes value judgments when making design decisions to optimise the value for the owner – the primary value subject of a building.

In addition to true value, Drevland et al. (2018) introduced a third term related to the perception of value: *Estimated value* – the value for the value subject by a second party judge – e.g. a designer for a client – given the judge's knowledge – both general and their knowledge of the values and context of the value subject.

THE VALUE JUDGMENT

We will use the term *value judgement* to refer to the evaluative judgment made to determine value. While the term is typically related to making moral judgments or people's behaviours, often the negative connotations, most dictionaries define the term broader. For example, the APA Dictionary of Psychology defines value judgment as "an assessment of individuals, objects, or events in terms of the values held by the observer rather than in terms of their intrinsic characteristics objectively considered" (American Psychological Association, n.d.). This definition aligns with what we already have covered on how people assess value. However, it assumes that the judge and the value subject are the same, and it goes beyond judging objects. Thus, here, we define value judgment as the evaluative judgment a value judge makes to determine the value of some object.

Referring to Figure 1., the value judgment is a matter of determining what value factors a value object provides on both the get and give sides of the scale and how they balance. However, doing so is less straightforward than it seems. We will discuss several aspects of the value judgment that make it so.

Value judgments consider experiences – not attributes or money

A fundamental aspect of value is that it is experience-based (Drevland et al., 2018; Holbrook, 1981). While people might sometimes express value factors in terms of object attributes or money, they will typically be placeholders related to the experiences they get from the value object. Say, for example, someone is buying a home. Superficially, they are giving up money and getting an asset in the form of a house or apartment. However, when it comes down to it, what factors people consider will be based on the experiences they envision having living there. For example: Will they sleep well there? Will they feel safe? Can they play loud music without annoying the neighbours? Can they host lavish dinner parties? How much time will they spend getting to and from work?

These examples are all factors impacted by the qualities of the home – i.e., the get side of the equation. However, similar considerations are related to the give side. Superficially they are giving up money. However, with few exceptions, money only matters if you do not have enough. For most people, what is important is how the mortgage payments will affect their life experiences. Can they dine out and go on vacations as often as they would like? Can they afford to keep up their hobbies? Will they feel safe financially with the burden of a mortgage?

With some twists, companies will make similar considerations as individuals (Drevland et al., 2018). First, people will consider what experiences they will have doing (or not doing) the activities that matter in their lives. Likewise, companies will consider their experiences doing the activities that matter to them – their business and production processes. Second, for companies, money can be of more direct interest. Typically, the *raison d'etre* for a commercial entity is to earn money for its owners or shareholders. In other words, one of the terminal values for a commercial entity is wealthy owners. For an individual, money is only ever a means to achieve their terminal values. However, being wealthy will directly support many terminal human values such as "freedom", "family security", and "social recognition".

The value judgment is comparative

One of the nine tenets of Drevland et al. (2018) is that value is comparative. They anchor this tenet in Kahneman & Tversky's (2000) seminal works on the human psyche, tying value to choices. However, they do not expand upon the implications of value being comparative.

Unlike objective value concepts – such as market value – our value concept does not have an absolute measurement. Value is the result of an evaluative judgment of what someone gets from an object and what they must give to obtain and use it. That result only ever makes sense in comparison to other such results. However, people make these comparisons in a broad sense. That is, one does not only compare apples to apples but also apples to oranges.

To take a more concrete example, when someone considers buying a specific home, they will compare it to other homes on the market; however, they will also compare it to alternatives such as renting or continuing to live at home with their parents. Regarding the previous point of value judgments considering experiences, the comparison is not between different objects but different sets of experiences.

The value judgment is holistic

People judge value holistically, not piecemeal (Drevland et al., 2018). Piecemeal judgment would entail judging each value factor individually, assigning them a weight, and then tallying them up. Doing so would be nonsensical for two reasons. First, assigning value factors a weight would require some measurement scale – thus, being incompatible with comparative value judgment, as described above. Second, how someone will weigh different factors is not linear. How much the various value factors weigh down on the scale will often depend on a complex interplay between them.

One caveat is that construction projects deliver complex objects with multi-faceted use. Here, one can, to some extent, consider the marginal value of distinct features such as a separate bedroom.

VALUE FACTORS

Having described and discussed the characteristics of the value subject and the value judgment that impacts value, it is time to revisit value factors. What factors do people put on the scale when making a value judgment of an object?

We would argue that the concrete factors one will consider will depend on both the value object and the value subject. For example, one will not consider the same factors when buying a car versus a home. There might be some overlapping ones related to, for example, financial aspects; however, the complete set of factors will differ widely.

Furthermore, for any given value object in our context – i.e., construction projects – there will be several stakeholders and thus value subjects. What an owner gives to and gets from a project is very different from what a contractor, user or neighbour does – and they can be in direct conflict with each other. For example, a developer might want to build an apartment building as tall as possible to maximise the monetary gain they experience; however, this might severely negatively impact the view of the neighbours and, thus, the experiences they have in their homes or places of business.

Experiences and placeholders

Value factors are grounded in experience. However, as pointed out, this might not be evident. People tend to describe placeholders rather than actual value factors. They relate desired object attributes that would provide them with some experiences rather than describe the desired experiences themselves. For example, someone buying a home might say they want a large backyard. However, nobody wants a large backyard for the sake of having a large backyard. They might want it because they enjoy gardening, want room for the kids or pets to play, or any other number of other experience-related reasons. Thus, “a large backyard” is, in this case, a placeholder for these experiences that the yard would support.

Regarding placeholders, money is a generic one (Drevland et al., 2018). Money can buy a lot of different experiences. One can go to the movies, dine out, vacation, etc. – or for a company; they can have various experiences through alternate investments.

While we have not conducted any in-depth study on the subject, with the advent of new value-centred delivery models, it is seemingly becoming more usual to explicitly link value factors to experiences rather than using attribute-related placeholders. For example, we know of one school project where one of the stated value factors was to reduce bullying and a psychiatric hospital where they wanted to reduce the use of force by 50%.

For an individual or a family buying a home, the use of placeholders is not a problem. However, in the domain of commercial and public projects, we would argue it can be. For example, an individual saying they want a large backyard is also the one making the decision on which home to buy. In a construction project, the people making the decisions can be several steps remove from those who describe the value factors.

An interesting example to illustrate the issue could be observed during the construction of St. Olav’s Hospital in Trondheim, Norway. When designing the doctor’s offices, they first asked the doctors what size offices they needed – and got back wildly varying size requirements. Then, they went back and asked what they needed to do office and what equipment they needed to do so. The doctors then explained that they, for example, would examine patients and needed an examination table. This experience-based description enabled the designers to develop office designs that fulfilled the doctors’ needs without being unduly large.

Classification schemes

Several authors have tried to establish classification schemes to aid in describing and understanding value factors in construction projects (Construction Industry Council, 2002; Drevland & Klakegg, 2017; Drevland & Svalestuen, 2013; Emmitt et al., 2005; Khalife et al., 2022). However, such frameworks all have their limitations. As discussed above, the factors considered in value judgment highly depends on both the value object and the value subject. Thus, such generic schemes are limited to relatively broad categories. They can serve as starting point to point one in the correct direction for describing value factors; however, they are in no way, shape or form fully fleshed-out tools able to adequately describe value factors in a given project.

SUMMARY OF TERMS

In the previous sections, we covered many different terms related to value and values. Terms we would argue are essential to understand the concepts of value and values properly. However, while the text explains all the terms, not all are given succinct and precise definitions. Furthermore, given how the paper presents the terms, we realise that getting a good overview of them can be difficult. Therefore, we have included Table 1 below to give an overview of the terms related to value and values the paper has presented.

Table 1: Summary of Terms

Term	Definition
Values / Human values / Organisation values	General beliefs about what is essential in life and how one should behave.
Terminal human/organisation values	Desired end states of an individual or organisation
Instrumental values	Beliefs that guide the behaviour of an individual or organisation
Value	The result of an evaluative judgment of what someone gets from an object and what they must give to obtain and use it
Value subject	The individual or organisation for whom the value of an object is considered
Value judgement	The act of determining the value of an object for someone through an evaluative judgment
Value object	The object that is considered when making a value judgment
Value judge	The person or group making a value judgement
Value factor	Factor considered on the get or give side of the scale when making a value judgement.
Perceived value	The value a value subject arrives at through making a value judgment themselves, given the knowledge that they possess
True value	The value that a value subject would arrive at through a value judgement if they possessed perfect knowledge
Estimated value	The value for a specific value subject judged by a second party with the knowledge that they possess

DISCUSSION AND CONCLUSIONS

The paper's purpose has been to untangle and clarify the concepts of value and value. In doing so, we have treated value and values – and the other introduced terms – as very stringent concepts. However, value is a common word in English, and everyday use does not abide by any such stringency. So, for example, someone might say some building feature provides great value for the owner. However, relating to the terms this paper has introduced, they actually mean that said feature supports one or more experiences that are significant value factors for the owner.

Enforcing such stringency and precision in everyday speech would be futile and counterproductive. People will still get their message across without any language policing. However, while low precision and ambiguous terms in everyday speech are acceptable, vague terms do not yield any precision in academic analysis and create poor foundations to build tools or more advanced theoretical constructs. Therefore, we would like to caution researchers who write about value or use the concept of value in their papers to be conscious of the difference between value and values, as well as different value concepts. We have too often seen authors trying to summarise what value is by picking various characteristics from papers dealing with vastly different concepts – often confounding value and values. Some of these authors end up concluding that value and multi-faceted concept. We would argue value should not be considered as such.

Take, for example, value, as this paper defines it, compared to the previously described concept of market value from economics. The two concepts are clearly related. Both centre on the relationship between what one gives and gets. However, the two concepts vastly differ in how one evaluates that relationship. Thus, we would argue that they cannot be considered facets of the same concept but are instead different concepts rooted in the same abstract root concept.

This paper has not gone into great depth on value and values in projects, mainly deferring to use examples at the personal level. There are two reasons for this: 1) To make it easier and understandable for the reader, and 2) we lack the appropriate knowledge.

The paper's purpose has been to foster the readers' theoretical understanding of the concepts, not to expound upon their real-world usage. Projects are complex sociotechnical systems. In addition to having a wide variety of stakeholders whose value must be considered, many stakeholders are, in effect, multi-headed trolls. They are not monolithic entities with a singular perception of value but a collection of individuals with many different value perceptions. Thus, discussing value in such a context complicates matters. The same holds for values. Therefore, we would argue that one must thoroughly understand the concepts at the individual level before one can grasp them at the organisational or project level.

Regarding not knowing enough about real-life values and values in projects, there is a shortage of empirical research on these matters – especially regarding what value factors are considered, how value judgments are made, and by whom. While a third of all IGLC papers mention value, very few go into detail on such matters. Those that do are not very useful due to a lack of terminological stringency.

We would argue that empirical data gathered from projects need to be analysed relating to a solid theoretical framework with unambiguously defined terms, such as what we have presented in this paper. Given how haphazard and ambiguous the everyday use of value-related terms is, any empirical statements gathered from projects need to be viewed and interpreted through such a lens to ensure internal consistency.

We are not as pompous as to believe that what we have is the end-all and be-all of the theoretical frameworks for value and value. However, we would strongly argue that research into value or values needs to relate to clearly defined terminology with a precision that is on the level of what we have presented in this paper. Otherwise, the results will be ambiguous mush, not serving to bring our field forward.

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CREATING CO-LOCATION CONCEPTS UNDER CONSIDERATION OF HYBRID APPROACHES IN CONSTRUCTION PROJECTS

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ABSTRACT

During the COVID-19 pandemic, across industries many project teams started working from home instead of their (co-located project) office, thus relying on virtual teamwork. This shift prompted the use of hybrid or virtual co-locations, whose purpose is to improve communication and collaboration in the project team. However, there is limited research on the effectiveness of these hybrid and virtual co-locations. A co-location can be implemented in both traditional and partnering delivery models, however, this research focuses on co-locations within partnering projects. To address this gap, interviews were conducted with co-location participants in Germany, Switzerland, and the US to gather a wide range of experiences, as well as supplement and validate the literature review. From this information, a co-location requirements catalog was created, and five concepts of co-location setups were identified and developed with varying degrees of hybridity. The research showed that trust and communication are crucial for collaboration, which is one goal of installing a co-location. Therefore, the implementation of a hybrid or virtual co-location must take this goal into account. In-person events play a key role in building and maintaining trust. As technology continues to advance, research on hybrid and virtual teamwork is becoming increasingly relevant.

KEYWORDS

Co-location, big room/obeya, collaboration, hybrid co-location, integrated project delivery (IPD)

INTRODUCTION

The COVID-19 pandemic sent many workers into home-office and virtual teamwork, including workers from the construction industry. The pandemic has resulted in the implementation of virtual and hybrid co-locations. The co-location is a procedure teams using collaborative project delivery models, such as IPD, implement (Lahdenperä, 2012). A co-location aims to foster communication, trust, and collaboration and can be implemented in traditional or partnering construction projects. However, there is a need to further understand co-locations, including hybrid and virtual variants, and their implications to have clear vocabulary for implementation

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and further research. This research seeks to address this gap in knowledge by investigating traditional co-locations, as well as hybrid and virtual derivatives, with a focus on the construction industry. The motivation for this research stems from the significant changes in work practices caused by the COVID-19 pandemic and the need to adapt to new modes of teamwork.

Figure 1 shows the structure of this paper. Each blue box represents a chapter, and the hexagons depict key points covered within the chapters. The introduction contains a brief overview of the paper. The results of the literature review covering the existing definitions of the co-location, goals, purpose, requirements, and concepts of a co-location. The method chapter explains the procedure of the literature review, as well as the gaps found, leading to the need for interviews. The following two chapters discuss the results of this paper: the five co-location concepts and the co-location as a method. Based on the interview results, the five identified co-location concepts found in the literature review were supplemented and explained in further detail. Additionally, in this research, we define the co-location as a method to encompass all five concepts. Finally, the closing remarks and conclusions wrap up and summarize the contents of this paper.

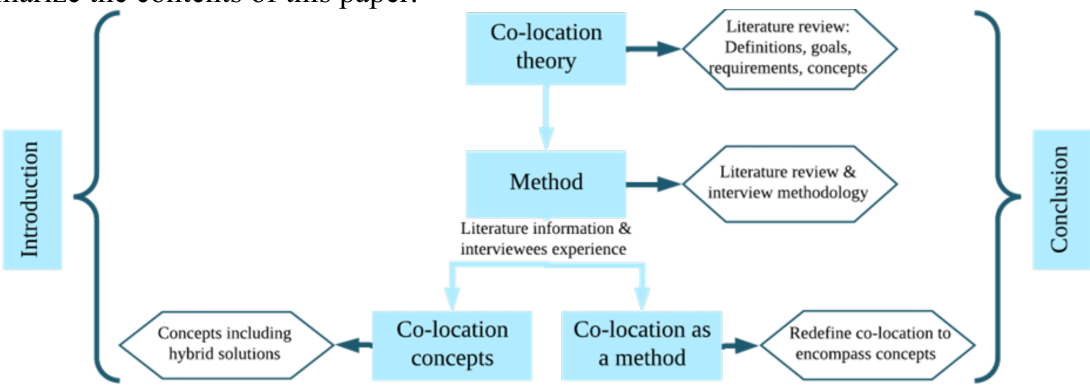

Figure 1: A Visualization of The Structure of This Paper.

CO-LOCATION THEORY

DEFINING CO-LOCATION

Often literature uses co-location, big room, and Obeya room interchangeably. However, they have different meanings and need clear differentiation.

A co-location in the construction industry refers to the practice of key members of a project working together in a shared space, usually a construction project office, to facilitate communication, teamwork, and productivity (Allison et al., 2018). This shared physical space, is designed to bring the team together to foster collaboration, create a group identity, and reach the goals of the project (Allison et al., 2018; Ashcraft, 1996; Fischer et al., 2017; Lazarte, 2020). Allison et al. (2018) mention it can be a physical or a virtual space. The co-location is not a universal requirement for all IPD projects, but research has found it to be an important factor in successful IPD projects (Haghsheno et al., 2022; Rodrigues & Lindhard, 2021). Although Hosseini et al. (2018) found the co-location to be the fourth most important partnering element in their research, only 6 of 43 projects observed implemented a co-location in Norway. Haghsheno et al. (2022) found three out of 13 international papers examined to believe a co-location is a must-have, and a further two mention the co-location as an optional element.

Obeya is an environment designed to facilitate the free flow of information and communication among team members and stakeholders, not a physical room (Dalton, 2019). It often includes visual management tools like charts, schedules, and trend lines to display the current status of a project (Liker & Morgan, 2006). Visual information management (VIM) is a tool used in Obeya to create transparency and transport relevant information to team members and display their work (Björnfot et al., 2012; Dalton, 2019). Obeya is derived from the Japanese word for "big room" and was originally used in the Toyota production system (Liker & Morgan, 2006).

The big room is a physical space where team members can come together to discuss and work on a project. The big room is designated as the design and coordination office of the project (Temel et al., 2019). Its purpose is to facilitate communication, collaboration, and innovation (Staun, 2020; Temel et al., 2019). The concept of the big room, however, is not clearly defined in the construction industry (Alhava et al., 2015). Obeya is a similar concept, but it specifically refers to an environment that supports the free flow of information and communication, not coordination. The big room is a part of the co-location and can contain visualizations inspired by the Obeya concept.

THE GOALS AND PURPOSE OF A CO-LOCATION

The co-location has a positive effect on integration and collaboration, which helps projects run more smoothly (Adamtey, 2019; Galvin et al., 2021; Mesa et al., 2019). The co-location aims to create a space that promotes collaboration and addresses challenges such as a large group of interdisciplinary people and the need for fast decision-making and information exchange (Allison et al., 2018). Figure 2 illustrates how the co-location facilitates collaboration, with the following paragraph containing the explanations of the connections.

The co-location enables fast decision-making and problem-solving through the exchange of ideas and discussions in the co-location (Allison et al., 2018; Bygballe et al., 2015; Galvin et al., 2021; Gomez et al., 2018). Effective communication and information exchange, aided by the physical proximity and presence of key partners in the co-location, is a factor in building relationships, trust, and collaboration (Adamtey, 2019; Ashcraft, 1996; Rahim et al., 2015; Thompson & Ozbek, 2012). Being present in the co-location allows for relationships to develop and for partners to gain an understanding of each other, leading to an increase of trust over time (Galvin et al., 2021; Olson & Olson, 2010). Trust is a prerequisite of teamwork, crucial for IPD projects, and needs to be consciously built from the start (Majava et al., 2019; NASFA et al., 2010). Performance indicators such as the percent plan complete (PPC) trend line can be tracked in the co-location to increase the team's reliability and commitment to project goals (Andary et al., 2020).

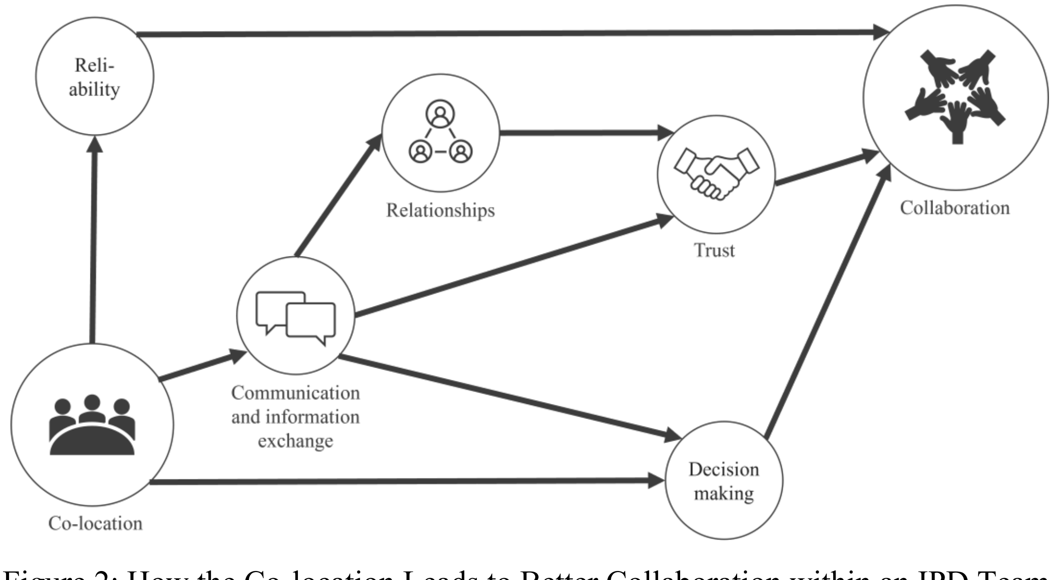

Figure 2: How the Co-location Leads to Better Collaboration within an IPD Team.

CO-LOCATION REQUIREMENTS CATALOG

Allison et al. (2018) outline a large list of considerations, attributes, and characteristics of a co-location. Knowing the requirements helps to fulfil the potential of a co-location. A co-location requirement can be a hard factor, like a conference room or a coffee machine, as well as a soft factor such as teamwork. The list created by Allison et al. (2018) is validated and supplemented during the literature review and interviews. Table contains the complete list and can be found in the appendix. The goal of this list is to aid those who want to set up a new co-location, so they can use this as a checklist throughout the creation of the co-location.

Not all requirements need to be considered at the same time, the categories are listed chronologically when which requirements need to be considered. The categories *Team/culture* and *Project organization* can begin in parallel to the remaining categories.

THE FIVE CO-LOCATION CONCEPTS

There are five overarching co-location concepts identified in the literature, sorted here by the amount of physical presence:

- *Full-time co-location*: completely in-person, 4-5 days a week at the co-location. Allow for the telecommuter (Fischer et al., 2017).
- *Part-time co-location*: 1-3 days a week at the co-location (Allison et al., 2018).
- *Pulsed co-location*: every other week or one week per month in the co-location. Focus on releasing work when in the co-location (Fischer et al., 2017).
- *Part-virtual*: an almost completely virtual co-location except for workshops which are done in-person (Hosseini et al., 2018).
- *Virtual co-location*: a virtual co-location with options for virtual or augmented reality (Fischer et al., 2017; Wolfartsberger et al., 2020).

A concept that can be combined with the above, is the *rotating co-location*. This is when the co-location is at one of the partner's offices and rotates between the various offices depending on the phase and needs of the partners (Fischer et al., 2017). The co-located *telecommuter* is when partners are allowed to work on other projects while present in the co-location (Fischer et al., 2017). For all concepts, except full-time, office hours need to be set. Establishing a clear schedule of when partners need to be present is imperative for a part-time and hybrid co-location to function (Fischer et al., 2017).

METHOD

The literature review covers the definition of co-location (A), existing co-location concepts (B), as well as the requirements and goals of a co-location (C). By using a Boolean search, numerous combinations of keywords were entered into various academic websites, such as sciencedirect.com and emerald.com. An example of a Boolean search being: (requirements OR characteristics OR value OR advantages) AND (co-location OR big room) AND (lean OR lean construction OR IPD). From the literature found, the sources that each author cited were also combed through for additional articles and potential sources. Publications include English and German articles. Literature was sorted into three categories listed above (A, B, C), and only included when within the context of the construction industry.

During the literature review, it became clear there are significant gaps in the available information regarding the co-location. To begin, co-location has several competing definitions and does not encompass the five co-location concepts, which we identified. Additional gaps found included points summarized here into six categories: (1) hybrid communication, (2) teamwork regarding hybrid co-locations, (3) co-location requirements, (4) digital solutions and alternatives, (5) reasons for a hybrid co-location, and (6) information on the degree of hybridity (DOH) within a co-location concept. Further gaps found that will not be covered further in this paper are as follows:

- Key performance indicators (KPIs) in a hybrid co-location
- Pedagogic view and psychological analysis of teamwork in hybrid co-location
- Minimum project size for a physical co-location
- Creating a co-location on a budget as well as co-location cost suggestions
- Social networks analysis (SNA) of the project team for co-location decisions
- Project quarterback rating (PQR) for assessing hybrid co-location performance
- Analysis of space needed in co-location based on people and budget size
- Effectiveness of concepts concerning collaboration, productivity, and planning using case studies

To address the gaps found in the literature review as well as supplement and validate the information found, a survey and subsequent qualitative interviews were conducted with co-location participants in Germany, Switzerland, and the US. Detailed interviewee responses to the six categories will not be covered in this paper. The goal of the interviews was to explore different perspectives and understand how participants tackled the challenges of the COVID-19 pandemic regarding the co-location. The interviews were semi-structured, explanatory interviews and structured into three blocks: introduction, main questions, and conclusion (Bogner & Menz, 2009; Gansen et al., 2011; Meuser & Nagel, 2009). This allows for the structure to keep the dialogue goal-orientated, but enough freedom to ask additional or clarifying questions.

A total of 41 people were contacted based on their experience with co-locations in the various project phases, 26 of whom agreed to participate in an interview in the months of February, March, and April of 2022. The participants included designers, builders, project owners, users, and coaches. Table 1 lists the project identity, position, and country of each interviewee. The German and Swiss interviewees represent seven IPD projects. Therefore, the results cannot be generalized to address traditional project delivery methods. The US interviewees were not based on a specific project, but rather on their general experience. Most of the interview partners were in the project management team (PMT), and some were in the senior management team (SMT) of their project. PMT and SMT definitions as well as corresponding names e.g. core team and alliance team will not be addressed in this paper. To ensure anonymity, the names, and companies of the participants, and their IPD projects, are not disclosed. The interviews were transcribed and analyzed using the qualitative content analysis method from Mayring (1991).

Table 1: An Overview of the Interview Partners.

Project	Builder	Lean Coach	Owner	Owner's represen tative	Designer	User's represen tative	Country
P1		1	1		2	2	DE
P2	2	1	2				DE
P3		2				1	DE
P4		2					DE
P5	1	1		1	1		CH
P6	2	2					DE
P7	1	1					DE
-	1	3	1				DE, USA

CO-LOCATION CONCEPTS

OVERVIEW OF THE FIVE CONCEPTS

With the information and experience of the interview partners gathered during the interviews, the five concepts found in the literature review were elaborated on and described in further detail. An overview of these five concepts can be found in Table 2. Due to limited space the results of the interviews will not be outlined, but rather the further development based off the interview results.

A co-location is hybrid when one or more team members are not physically present, and the rest is physically present. The DOH peaks when there are several participants in the co-location but also several working remotely on the none-core days. A co-location becomes virtual when all members are joining in virtually. The concepts have varying degrees of hybridity, beginning with a full-time face-to-face (F2F) co-location with close to zero hybrid components. Then the hybridity is increased and peaks at concept 3, the pulsed co-location. In concepts 4 and 5, hybrid components are replaced by virtual components. Components are processes that happen within the co-location, such as meetings and workshops, as well as requirements listed in the requirements catalog.

Table 2: An Overview of the Co-location Concepts with Varying Degrees of Hybridity.

Concepts	Concept 1 Full-time	Concept 2 Part-time	Concept 3 Pulsed	Concept 4 Part-virtual	Concept 5 Virtual
Picto-grams					
Physical presence in days a week [d/w]	4-5 d/w	1-3 d/w	Every other week or one week per month	Select processes in person, everything else is virtual	0 d/w Completely virtual
Options	Tele-commuter		Possibility for a rotating co-location	Virtual or augmented reality	Virtual or augmented reality
DOH	Low	High	Medium	Low	Low

The goal of a hybrid or virtual co-location is to maintain at least the same level of collaboration as a traditional F2F co-location. This section covers the created concepts proposed to reach this goal.

The process of choosing a concept depends on different project framework conditions such as the size of the project both in costs and complexity, as well as the phase of the project. Due to the diversity of project conditions in the construction industry, there is no one size fits all solution for choosing a concept. The decision on which co-location concept depends on the project framework, such as budget, complexity, duration, and the current project phase. It also depends on the chosen team and if they are compatible with a high DOH.

CONCEPT 1: FULL-TIME CO-LOCATION

This concept encompasses the traditional F2F co-location. This is where all project partners come to the co-location in-person, 4-5 days a week. This concept has a low DOH. The *telecommuter*, as described above, is when project partners can work on other projects while at the co-location. Note that it is not recommended to force partners to come five days a week as this goes against the new normal. If five days a week are needed, create a shift system where the first half of the team is there Monday-Thursday and the second half Tuesday-Friday. To implement this concept, the full standard co-location requirements catalog is required. Table in the appendix contains the catalog, including both requirements found in the literature review as well as during the interviews. The full-time co-location is suggested mainly during the construction phase for large and complex projects. During the construction phase, the co-location should be as close to the construction site as possible, in the earlier phases it can be located closer to the team's offices.

CONCEPT 2: PART-TIME CO-LOCATION

The second concept is a part-time co-location averaging 1-3 core days a week in-person and the rest in a hybrid or virtual setup. Team members are allowed to work in the co-location on the non-core days if this is what they prefer, but they are not required to be present. This concept is by far the favored concept based on the interviews. This concept is the sweet spot between F2F and virtual. It allows for the benefits of a physical co-location while still giving the flexibility of a concept with a higher DOH. Here a physical co-location is necessary that follows the same requirements and steps as in Concept 1. Additionally, to the full-time requirements, the part-time co-location needs hybrid components. For this concept, it is recommended to do LPS in person but have a digital copy so that on the days away from the co-location participants can still access this information, especially when only using the co-location 1 or 2 days a week. The team should either use software that allows interactive work in the big room or have the physical post-its copied into a digital version after each LPS meeting, which could be as simple as uploading photos. This depends on the team and whether they chose to invest in software and how affine they are with technology. VIM should be present in the co-location; however, the project should have an additional dashboard online as well to quickly access the current project status. Most meetings, including SMT, PMT, and PIT meetings are all in-person at the co-location. Organizational and simpler topics can be held in a hybrid or virtual format. Meeting rooms need to be equipped with appropriate hardware such as microphones, screens, and cameras to be able to hold hybrid meetings.

CONCEPT 3: PULSED CO-LOCATION

The third concept is the pulsing co-location. This means that a team is either at the co-location every other week or one week per month. The week where presence is mandatory are the so-called core days for this co-location. Depending on the team it may only be 3 days a week, once a month. It is possible to have a rotating co-location, which, as described above, is when the co-location rotates between the partner's offices and does not have a separate location. If there is a separate co-location and not a rotating co-location, each team member can choose for themselves whether to be present on the non-mandatory weeks. Due to the low amounts of mandatory presence, other processes increase in importance and must compensate for the time missing in the physical co-location. It is important to have a cohesive virtual dashboard to maintain VIM even when not present in the co-location, this can be a virtual whiteboard software or integrated with the BIM model. LPS meetings are done in a virtual format. Note that due to the large number of participants in a LPS meeting, it is suggested to be completely virtual to avoid miscommunication. The importance of LPS meetings increases with the DOH as it allows for the whole team to come together and communicate what is currently being worked on. This concept has the highest DOH, meaning most of the co-location aspects are in a hybrid format.

CONCEPT 4: PART-VIRTUAL CO-LOCATION

The part-virtual concept is ideal for smaller projects or project phases that require less collaboration. The team should meet in person for select processes that enable the team to still build trust and relationships that in turn allow for open communication and collaboration. In-person events, like team building events and the kick-off, are even more vital for this concept as they are the few times the team comes together. Team building events need to be reoccurring to maintain the level of collaboration. These events can either be done at the partner's offices, or in event rooms rented for those specific occasions. All other processes are done virtually. This includes SMT and PMT meetings, as well as LPS meetings. Facilitation and leadership skills are of higher importance here to ensure the team is still collaborating and getting along. The team needs to have clear communication and meeting rules, as well as more discipline than using a traditional co-location. This co-location form is almost completely virtual, and therefore, the DOH sinks.

CONCEPT 5: VIRTUAL CO-LOCATION

The last concept is the completely virtual co-location. This has no in-person or hybrid aspects. The virtual co-location is currently not recommended. Due to the missing in-person interactions, it is difficult to build trust, communication, and therefore, collaboration. This concept should only be implemented if the team is a small tight-knit group that has experience working together. Due to chance communication missing entirely, other communication channels as well as VIM need to carry more weight. Set importance on video calls with the camera and microphone on, rather than chat platforms. This maximizes the number of communication styles in use. Options for virtual or augmented reality can help further increase the number of communication styles being transmitted. A virtual dashboard that is clean, structured, and contains all important project status information in one accessible place is vital. Software needs to be intuitive and available to all team members. Ideally, a communication platform is used that encompasses everyday communication, the project dashboard, the LPS, the BIM model, the master schedule, and other relevant information.

CO-LOCATION AS A METHOD

Due to the terms co-location, big room, and Obeya room being used interchangeably, as well as the definitions not encompassing hybrid or virtual co-locations, we expand the definition of the co-location. To create clarity, we define co-location as follows:

The co-location is a method of transforming a space to bring a team together and foster collaboration through coordination, visualization, and transparency. It is the space where interdisciplinary teams come together to collaborate, communicate, and work as an integrated team side-by-side. This includes all hierarchies, e.g., in IPD projects the project implementation teams (PITs), PMT, and SMT. The co-location uses visualizations to inspire the team, using the principles of the Obeya room throughout the space. The co-location does not have to be a permanent physical space in the case of a hybrid or virtual co-location.

By defining the co-location as a method, rather than a physical space, hybrid and virtual co-locations can be considered. For smaller projects, the physical co-location may just be a big room including the workstations of the team. Larger projects will encompass the big room as well as meeting rooms, a coffee corner, and an open co-working space.

CONCLUSIONS

Creating a high-performing team of interdisciplinary, cross-functional people in a complex construction project needs trust and open communication. The co-location is a tool that improves collaboration and communication in construction projects. A co-location includes various components such as VIM and LPS, as well as elements like acoustics and the Internet. Due to the COVID-19 pandemic and the parallel transformation of technology, it has become the new normal for companies to offer employees more flexibility to work from home (Raghavan et al., 2021). A hybrid approach to co-location has become increasingly important, combining in-person and remote work. A co-location must have the fitting components and be used effectively to be successful. Based on the literature review, supplemented, and validated through the interviews, a comprehensive requirements catalog was created and can be used as a checklist for future co-locations.

We defined co-location as a method to transform a space to bring an interdisciplinary team together and foster collaboration through coordination, visualization, and transparency. The co-location does not have to be a permanent physical space in the case of a hybrid or virtual co-location. Depending on the size of the project, a co-location can be as small as the big room or large enough to include the big room as well as smaller meeting rooms, a coffee nook, and an open co-working area. The co-location actively uses visualizations to inspire and guide the team, using concepts of the Obeya room throughout the space.

Five co-location concepts were identified in the literature review and developed further with clear definitions, three of which are hybrid. By defining each concept clearly, future discussion over the concepts will have fitting vocabulary. The second concept, being the most recommended in the interviews, is a part-time co-location where participants are present 1-3 days a week depending on project size and preference. These concepts should be seen as suggestions and need further examination to understand their impact on collaboration, teamwork, and the project. They are based on 26 interviews and a literature review. The interviews were held mainly with co-location participants in Germany, findings here cannot be generalized for international purposes.

In conclusion, interviews showed hybrid co-location concepts can be successful, however, none recommended the long-term implementation of a virtual co-location. Interviews showed that in-person events need to be at the beginning and throughout the project to build and maintain trust. As the DOH increases, communication channels such as chance communication decreases. Interviewees argue other communication channels such as LPS need to compensate for the missing communication.

The co-location concepts need to be further analyzed and tested in practice to ensure their accuracy. Each project is different, and no co-location is the same. Further differentiation needs to be taken based on the project's size, both in volume as well as in the number of project participants. Additional sources of information could be included in the future, such as case studies and large-scale surveys to gain more practical data. Further international interviews should be held to ensure the accuracy of these findings and to remove cultural biases.

A process and research of a topic are never complete. As lean methods would say, one needs to constantly plan, do check, and act (PDCA). This paper covers one iteration of co-location concepts that are built on prior research and practical implementations. We recommend that in the next iteration, these concepts be, implemented, checked, and further improved.

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APPENDIX

Table 3: A complete catalog of co-location requirements and characteristics, as found in the literature review and the interviews. Italics: new findings, not mentioned in the literature.

Categories	Requirements	Literature source	Unique mentions
Team/culture	Team compatibility/cultural fit	AIA California Council, 2007	4
	Collaboration mindset		2
Project organization	Clear and fair MPC	Pishdad-Bozorgi, 2017	
	Project charter	Allison et al., 2018	
Region	Proximity to team offices	Allison et al., 2018	
	Proximity to site	Allison et al., 2018	1
Attributes	Bright	Allison et al., 2018	2
	Flexible	Allison et al., 2018	1
	Comfortable	Allison et al., 2018	
	Accessible and safe	Allison et al., 2018	
	Colorful		1
	Quality		1
	Open design		5
Environment	Natural light/lighting	Allison et al., 2018	3
	Ventilation	Allison et al., 2018	1
	Temperature	Allison et al., 2018	1
	Acoustics	Allison et al., 2018	5
	Weather protection	Allison et al., 2018	1
Rooms	Kitchen access	Allison et al., 2018	9
	Break-out rooms	Allison et al., 2018	13
	Big room	Allison et al., 2018	8
	Shape and size of space	Allison et al., 2018	2
	Washrooms, room for coats/boots	Allison et al., 2018	
	Recreational area		3
Functionality	Wall space	Allison et al., 2018	5
	Partition walls	Allison et al., 2018	3
	Furniture/furnishing/layout	Allison et al., 2018	4
	Storage	Allison et al., 2018	
Technology	Audio/video	Allison et al., 2018	3
	Internet	Allison et al., 2018	6
	Projectors	Allison et al., 2018	2
	Computers	Allison et al., 2018	6
	Software	Allison et al., 2018	
	Modern IT		5
Co-location organization	Rules of engagement	Allison et al., 2018	1
	Seating arrangement	Thompson & Ozbek, 2012	2
	Celebrate success	Allison et al., 2018	1
	Shared learning/workshops	Ashcraft, 1996	1
	Clear purpose/goals	Pishdad-Bozorgi, 2017	2
	Psychological safety	Ebrahimi & Dowlatabadi, 2019	2
	Coffee/tea/snacks	Allison et al., 2018	
	Visual information management	Ashcraft, 1996	9
	Regular PMT project updates		1
	Sense of added value		2
	Respect among partners		1
	Workshop material		1
	Clean/organized		1

Cardenas Castaneda, J.A., Barkokebas, B., Martinez, P., & Ahmad, R. (2023). “Flexible robotic production in modular construction: a lean approach.” In: *Proc. 31st Annual Conference of the International Group for Lean Construction (IGLC31), Rybkowski, Z. K., Liu, M., and Sarhan, S. (eds)*, Lille, France, pp. 595–606. doi.org/10.24928/2023/0247. Available at: <https://iglc.net/Papers>

FLEXIBLE ROBOTIC PRODUCTION IN OFF-SITE CONSTRUCTION: A LEAN APPROACH

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ABSTRACT

The integration of robotics into flexible manufacturing systems (FMS) has been identified as a potential strategy for increasing modular construction flexibility. The purpose of this paper is to present a conceptual framework for investigating the relationship between FMS and robotics in modular construction. The framework proposes that by incorporating robotics into FMS, prefabricated building component manufacturing systems will gain flexibility. The two key variables of the framework are robotics (as the independent variable) and FMS (as the dependent variable). Moderator variables such as controlled environment and variability are also considered, as are mediator variables such as real-time adjustments, productivity, equipment utilization, set-up times, varying speeds, and reduced manpower. The purpose of this paper is to set the theoretical foundation for further studies on robotics integration into FMS in modular construction. The paper concludes with a discussion of the proposed implications of the framework for modular construction practitioners and researchers.

KEYWORDS

Construction 4.0, modular construction, robotics, flexible manufacturing systems.

INTRODUCTION

Modular construction is a method of manufacturing and construction that involves prefabricating building components in a controlled environment before assembling them on-site. It is based on the concept of modular product architecture, which entails designing products in such a way that they can be easily customized and configured using pre-designed modules (Bertram et al., 2019). However, the industry's main problem is a mismatch between the need of large type batch sizes in fabrication and the needs of small type batch sizes in assembly. This results in excess inventory or missed opportunities to meet customer demand, both of which can negatively impact the company. In the absence of robotics in modular construction fabrication, the industry faces one of the major challenges of manufacturing, the inability to adjust production time to meet changing demand for a product (Wadhwa, 2012).

Flexible Manufacturing Systems (FMS) is a collection of manufacturing technologies that allow for the quick and efficient production of a wide range of products in small batches. FMS technologies such as computer-controlled machining centers, automated material handling

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systems, and robotics are designed to work together to enable the efficient production of a wide range of products with minimal changeover time. FMS offers a cost-effective option for small-batch production while retaining the efficiency and productivity of mass production (Kostal et al., 2014).

The use of robotics in modular construction fabrication can help to address this issue. Robots can work around the clock by automating production processes, increasing productivity and reducing the need for manual labor. Robotics also allows for the quick and easy adjustment of production schedules to meet changing demand, making it easier to respond to market demands. Furthermore, the use of robotics can improve the consistency and accuracy of the manufacturing process, resulting in higher-quality products (Tilley, 2017).

The ability to adapt to fluctuating demands has become a critical factor for success in the 4.0 Industry era (Enrique et al., 2022). This requires production lines to be able to adapt to the demand changes. These changes in product demand occur in the market as a result of customer requirements changes (Yadav & Jayswal, 2018). The modular building industry has to deal with lean implementation challenges such as product customization flexibility and variable market demand (Innella et al., 2019). Companies must prioritize flexibility and the ability to respond quickly to changes in demand in order to remain competitive.

Despite the increased productivity brought by offsite construction involving efficiency, there is still improvement to be done. A lot of focus has been placed on using various methods for improving productivity but there have been a few emphases on incorporating automated systems into the offsite manufacturing process (Tehrani et al., 2022). The World Economic Forum has created three scenarios for the future of construction, each of which addresses a different megatrend, including the integration of robotics and pre-fabrication (Pan et al., 2022). Additionally, legislative bodies like European Parliament have emphasized the importance of robotics as a key piece for the digital transformation of the construction industry (European Parliament, 2019).

While there are challenges associated with implementing robotics in modular construction fabrication phase that is illustrated in Figure1, the benefits of increased productivity, reduced dependence on labour, improved responsiveness to changing demand, and improved product quality make it a promising technology for the future of the modular construction industry. The purpose of this paper is to present a conceptual framework for investigating the relationship between modular construction and flexible manufacturing systems (FMS). The paper also intends to provide the theoretical groundwork for future research on robotics integration into FMS in modular construction.

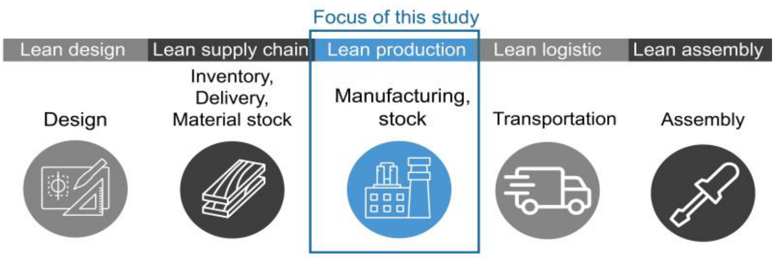

Figure 1: Production Stages in Modular Construction (Innella et al., 2019).

SYNERGIES BETWEEN FLEXIBLE MANUFACTURING SYSTEMS AND ROBOTICS

BENEFITS AND CHALLENGES OF FLEXIBLE MANUFACTURING SYSTEMS

A flexible manufacturing system (FMS) is regarded as an essential component in the realm of Industry 4.0, as it has the potential to improve system performance and thus boost the system's overall competitiveness (Priyadarshini & Gupta, 2023). As the name implies, it is characterized by its flexibility, which allows it to respond quickly to changing production requirements and conditions. An FMS is made up of adaptable machines such as robots, multi-purpose machines, or workstations, an automated transport system, and a decision-making system, also known as a scheduler, that determines which tasks will be executed and on which machine at any given time (Eloundou et al., 2015).

One of the most significant advantages of an FMS is that it allows the system to adapt to changes in demand, reducing downtime and increasing productivity (El-Khalil & Darwish, 2019). A manufacturing system's adaptability allows it to handle varying levels of product variety and quantity (Priyadarshini & Gupta, 2023). Considering that flexibility is highly important when producing for a fluctuating demand, FMS concept aims to bridge that gap. Other benefits include increased capital and equipment utilization, shorter work-in-process and set-up times, faster throughput and lead times, smaller batches and lower inventory, and fewer manpower requirements (Magalhães et al., 2022).

However, there are some challenges associated with implementing flexible manufacturing systems, such as low equipment utilization, a lack of technical expertise, and a lack of understanding on the part of senior management, all of which can have a negative impact on the FMS's implementation and execution (Priyadarshini & Gupta, 2023). Furthermore, the cost of implementing and commissioning a flexible manufacturing system is high, and the anticipated savings are difficult to quantify (Magalhães et al., 2022).

BENEFITS AND CHALLENGES OF ROBOTICS

Another key driver for Industry 4.0 is robotics (Bahrin et al., 2016), which is a rapidly growing field that has the potential to revolutionize the way products are manufactured and produced. The implementation of robots in various industries is gaining widespread recognition for its ability to improve productivity, efficiency, and reduce the need for manual labor, particularly in repetitive or hazardous tasks. Robots come in a diverse range of shapes, sizes, and functionalities, which can range from highly flexible and autonomous to being limited to performing a single or set of predetermined tasks (Smids et al., 2020).

There are two important types of robots that are relevant to this research: industrial robots and collaborative robots. Industrial robots are heavy rigid bodies that perform a complex series of actions that for a human would be very difficult and dangerous to do, such as for example carrying a huge load and are normally placed in a human-isolated workspace. On the other hand, we have collaborative robots, also known as cobots, that are smaller, more flexible and designed to operate close to humans within the same space (Sherwani et al., 2020).

The benefits of robotics in manufacturing and production are numerous. For instance, robots are capable of mass customization through the production of lots as small as single unique items because of the ability of rapidly configure machines to adapt to customer-supplied specifications. Furthermore, robots provide a high flexibility feature to the production, since they can produce new products quickly without complicated re-tooling or setup of new production lines (Bahrin et al., 2016). Additionally, robots bring the benefit of working 24/7 without breaks, leading to increased productivity and reduced downtime (Naveen Reddy et al., 2019). Furthermore, robots can perform complex tasks with a high degree of accuracy, reducing the likelihood of human error and improving product quality. Additionally, robots can work in hazardous environments, reducing the risk of injury to human workers.

However, there are also some challenges associated with the implementation of robotics technology. For instance, the high cost of acquiring and maintaining robots can be a barrier for smaller businesses, additionally the total costs are often no completely predictable during the beginning stage of the project, which might increase due to unexpected follow-up costs, for example for employee training (Flechsig et al., 2022). Moreover, the lack of technical expertise related to the operational side of the robots can limit their widespread adoption.

In conclusion, while robotics technology holds great promise for the manufacturing and production industries, it is important to carefully consider the benefits and challenges of implementing robotics, in order to maximize its impact and minimize any negative effects.

FLEXIBLE MANUFACTURING SYSTEMS WITH ROBOTICS IN MODULAR CONSTRUCTION

Modular construction has a strong connection with manufacturing as it involves the production of prefabricated building components in a controlled environment (Bertram et al., 2019). These components are then transported to the construction site and assembled, reducing the time and effort required for traditional on-site construction methods (Kamali & Hewage, 2016). This approach aligns with the principles of Industry 4.0, which prioritizes the use of advanced automation and technology to increase efficiency and quality in the manufacturing process (Bahrin et al., 2016).

Modular construction uses panels that are cut to the desired shape and size using CNC (computer numeric control) tools that can cut in almost any direction with high precision to form openings, service voids, etc. A CNC system is designed to perform specific tasks by following precise instructions. Figure 2 illustrates how the CNC system for manufacturing components for modular construction works, following a set of steps that are already programmed. However, the main drawback of this type of system is its inflexibility, since it lacks the ability to adapt to changes in its environment, modify its process, or make independent decisions (Virasak, 2019). This is the main distinction between flexible systems and a CNC sysstem.

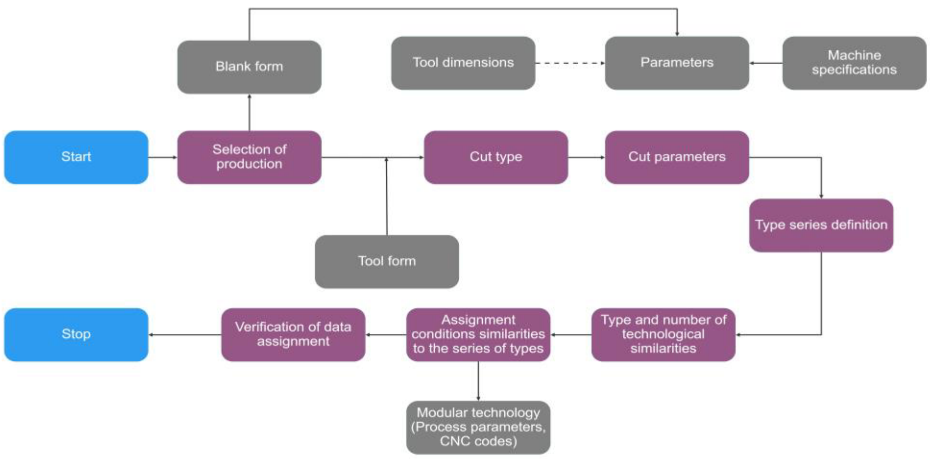

Figure 2: CNC Manufacturing Process of Modular Construction (Rząsiński, 2018).

A flexible system can alter its process, change its instructions, and make decisions based on input or feedback (Lafou et al., 2016) while a CNC only follows the instructions that have been programmed into it. On the other hand, robotics systems are considered to be more flexible compared to other manufacturing processes. One reason is robotics systems can be programmed to perform a wide range of tasks (Graetz & Michaels, 2018), making them adaptable to changing manufacturing needs. Furthermore, robotics systems often feature sensors and feedback systems that allow them to make real-time adjustments to their operations.

Production fluctuations are a common occurrence in manufacturing as illustrated in Figure 3. The graph depicts the fluctuations in demand for prefabricated components in the modular construction industry. The graph shows how demand for prefabricated components has changed over time, with peaks and troughs. Understanding these fluctuations is critical for industry stakeholders because it can help inform production, inventory management, and pricing strategies. This graph is a useful visual representation of the industry's demand patterns that can be used to represent demand fluctuations.

The demand for a manufacturing plant can vary from day to day (Ojha et al., 2013), making it unnecessary to have a 100% production capacity all the time. A low-demand rate is translated to high-demand variability, which leads to an inefficient manufacturing process as a consequence of high tooling and setup costs (Knofius et al., 2016). From a lean perspective, demand fluctuations during the production of modular construction components result in overproduction, known as an example of waste in the lean approach. Longer lead times, higher carrying costs, and extra inventory can all be the effects of overproduction (Aziz & Hafez, 2013).

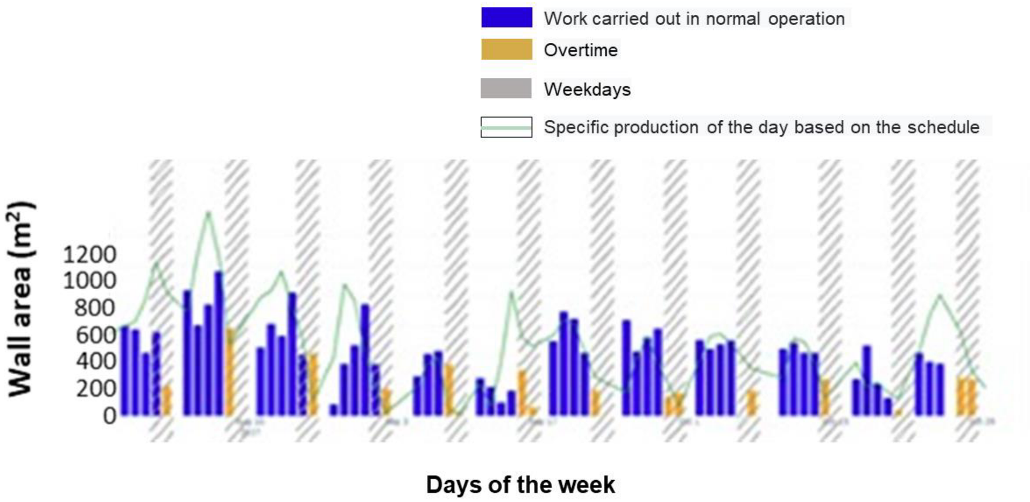

Figure 3: Fluctuation in Modular Construction Industry Demand for Prefabricated Components.

This is why flexibility in production is a key challenge in the industry. By understanding the demand variability, manufacturers can adjust their production processes to accommodate these fluctuations, reducing the need for maximum efficiency at all times. This can help save costs and resources, while still meeting customer demands. To maintain the principles of Lean, it is essential to have a flexible and responsive manufacturing system that can adjust to changing demand and avoid overproduction.

The integration of FMS with robotics in the modular construction field has several benefits. One of the main advantages we can obtain from the combination of these two, is increased production and efficiency. The use of robotics in this field enables the production process to be smoother and uninterrupted, even when faced with fluctuations, as robots can adapt to the varying speeds and production requirements. Additionally, with robotics the speed with which a product can be produced has improved, as digital designs and virtual modelling of the manufacturing process reduce the time between product design and delivery (Bahrin et al., 2016). This combination of FMS and robotics provides a powerful tool for the modular construction industry to optimize production and increase overall efficiency.

Optimization for modular construction topics has become increasingly important as the construction industry looks to build faster while also balancing the need for efficiency. In some cases, the focus on speed can be beneficial, but in many others, it may not align with the actual demand of a manufacturing plant and the variability in demand on a daily basis. Implementing flexible manufacturing systems (FMS) with robotics can address these challenges by increasing production and efficiency, allowing for adaptation to different speeds and production times as well as reducing the time between product design and delivery (Smids et al., 2020). Additionally, the integration of FMS and robotics can help to optimize operations and reduce downtime, leading to greater efficiency and cost-effectiveness (Bahrin et al., 2016)

The integration of flexible manufacturing systems (FMS) with robotics has several benefits in the field of modular construction. One of the most significant advantages of combining the two is reaching non-stop production. With the use of robotics, these can be adapted to speed changes and respond quickly to the current demand and fluctuations of the manufacturing facility, resulting in a production that is targeting the efficiency it needs.

One of the main obstacles to integrating lean in the modular construction industry is increased variability (Innella et al., 2019). FMS allows for quick adaptation to changes in demand, making it possible to handle varying levels of product variety and quantity. When combined with robotics, this flexibility becomes even more powerful, as the robots can respond quickly to changing production requirements and conditions. This leads to improved production performance, use of assets, and overall competitiveness in the market.

Moreover, the use of robotics in FMS can reduce the need for manual labor, leading to increased safety and reduced risk of injury. The integration of robotics also leads to improved equipment utilization, shorter work-in-process and set-up times, faster throughput and lead times, smaller batches and lower inventory, and reduced manpower requirements (Magalhães et al., 2022). Additionally, robotics systems can be quickly reconfigured to perform various tasks and multiple tasks (Pedersen et al., 2016), reducing the setup time and making them more flexible to handle a variety of manufacturing needs. While CNC systems are well suited for applications that require high precision and repeatability, robotics systems offer greater flexibility, programmability, and adaptability to changing manufacturing needs.

In conclusion, the combination of flexible manufacturing systems and robotics in modular construction presents numerous benefits, including increased production speed and efficiency, improved system performance and competitiveness, reduced need for manual labor, and increased safety and equipment utilization when producing panels for modular buildings. By leveraging the benefits of both FMS and robotics within modular construction, the industry should be able to better manage the fluctuations they have to face day by day and improve overall production efficiency.

CONCEPTUAL LEAN FRAMEWORK

The challenge addressed in this paper is that modular construction has a continuous change in demand, on a day-to-day basis, as is illustrated in Figure 3 which showcases an example of the variability of demand across a small period (months) for a modular construction facility. The ability to respond and adapt to changes in demand is essential to stay competitive and following lean principles. Furthermore, this variability also creates inefficiencies relating to overproduction at the system and line levels, incurring wasted efforts to deal with inventory or delays (Aziz & Hafez, 2013). Thus, a fluctuating demand requires a flexible and agile approach to production and a system that can adjust to these changes in real time is ideal to minimize wastes related to production timing.

To address this challenge, the integration of robotic flexible systems within modular construction is considered a strategic approach. A conceptual theoretical framework is developed to represent the relationship between flexible manufacturing systems (FMS) and robotics in modular construction. The focus of this study is to determine the feasibility of incorporating flexible robotics systems into modular construction processes.

A visual conceptual framework is a visual representation that outlines the key relationships among variables in a study. In such a framework, the independent variable is manipulated or changed in an experiment, the dependent variable is the variable that is being measured and is expected to change as a result of the manipulation of the independent variable. The moderator variable is a variable that influences the relationship between the independent and dependent variables, while the mediator variable is a variable that explains the relationship between the independent and dependent variables. The control variable is kept constant in an experiment to prevent it from interfering with the results and to isolate the effect of the independent variable on the dependent variable (Swaen & George, 2022).

In this conceptual framework illustrated in Figure 2. The relationship between the independent variable (robotics) and the dependent variable (modular construction flexible manufacturing systems) is understood through mediator variables. These variables act as intermediaries to explain how the independent variable impacts the dependent variable. The mediator variables selected in this framework are real-time adjustments, accuracy, equipment utilization, set-up times, varying speeds, reduced manpower, and implementation cost. These variables were selected as a result of the literature review to provide a thorough understanding of the impact of robotics on modular construction flexible manufacturing systems.

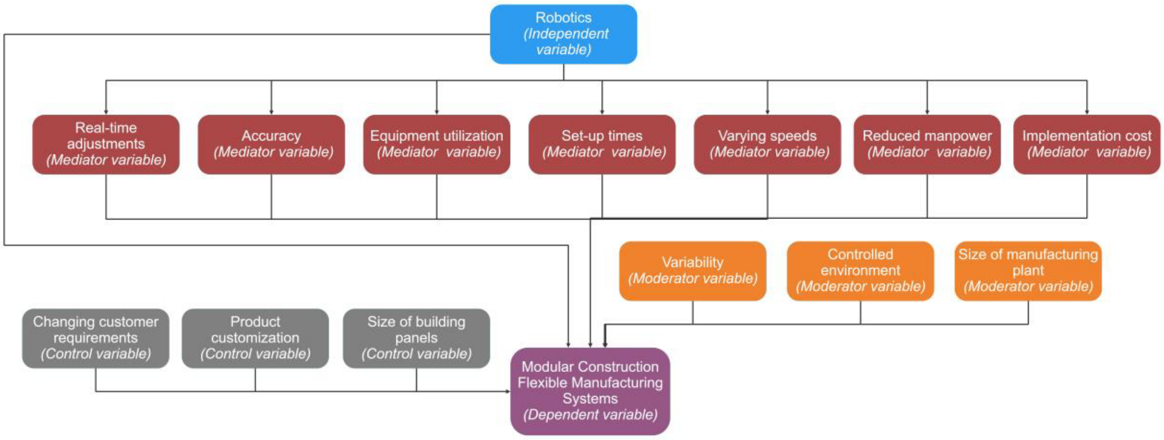

Figure 4: Conceptual Framework Robotics – Flexible Manufacturing

The selection of these specific mediator variables in the present study was based on a previous research article that established the connection between lean concepts and robotics (Cardenas et al., 2022). Specifically, the paper proposed a matrix model that described how the design parameters for a robotic cell in offsite construction interact with major lean wastes. This matrix model identified various design parameters related to robot selection criteria, production requirements, and cell requirements, which were identified through extensive literature reviews and observations of industrial robotic cells.

The variable "equipment utilization" in the framework is linked to the robot selection criteria of the matrix, as the choice of the robot can affect the efficiency and productivity of the production process. The variable "varying speeds" is linked to the production requirements of the matrix, as the speed of the production process can be affected by factors such as robot speed and cycle time. The variable "real-time adjustments" is linked to the cell requirements of the matrix, as the design of the cell and the robots used can affect the ability to make real-time adjustments to the production process. The variable "reduced manpower" in the framework may is linked to lean waste, as the use of robots can reduce the need for human labour and potentially reduce waste.

Real-time adjustments highlight the ability of robotics to make on-the-spot changes to production processes, while accuracy measures the precision of the production process. Equipment utilization, set-up times, and varying speeds demonstrate the efficiency of the production process. Reduced manpower and implementation costs provide insight into the impact of robotics on the workforce and overall cost of production. Together, these mediator variables help to illustrate the relationship between robotics and modular construction flexible manufacturing systems.

These variables have the potential to alter the level of flexibility in manufacturing systems. Variability in the manufacturing process is particularly important as it can significantly impact the flexibility feature. When variability is high, it can pose a challenge to the flexibility of manufacturing systems, whereas low variability scenarios may offer more flexibility. The level of control in the environment and the size of the manufacturing plant are also important factors that can impact the level of flexibility.

Furthermore, time is considered a control variable because it is held constant to prevent interference with the results. Although time is not the primary focus of the study, it can still impact the results. In the context of flexible manufacturing, a set period of time is used to produce a certain number of panels. However, demand can change unexpectedly, and the production process may need to be adjusted accordingly. This adjustment in production time can impact the flexibility of the system as it affects the production rate and the ability to adapt to changing demands. Hence, it is crucial to carefully manage time in flexible manufacturing systems to ensure that they remain efficient and flexible even in changing conditions.

The focus of this study is on the importance of flexibility in modular construction, as opposed to solely focusing on productivity. In the context of lean production, flexibility is valued more highly than productivity as it allows for the necessary amount to be produced at the right time. The current state of CNC systems in modular construction, which execute repetitive tasks in a fixed order and lack adaptability to changes, results in overproduction and is considered waste in the lean philosophy (Chahal & Narwal, 2017). Our proposed system offers a solution that prioritizes flexibility and the ability to produce the necessary amount at the necessary time, aligning with the principles of lean production.

CASE STUDY

This study compares the production of a cross-laminated timber (CLT) panel for modular construction using a robotic machining cell and a CNC machine. The study aims to determine which manufacturing process is more efficient and adaptable to changes in product design and production sequence.

The CLT panel has a variety of geometrical shapes for windows and doors, as well as additional features unique to CLT building techniques for modular construction. A previous robotic design for CLT machining is used to obtain simulated results (Villanueva et al., 2021), whereas the same CLT panel is then simulated in Fusion 360, illustrated in Figure 6 using a CNC machine to compare the two manufacturing processes. The specifications considered for the CNC simulation are a working area of 13500mm width, 1956mm height and 4648mm depth. Additionally, a rapid traverse speed of 63.5 MPM, cut speed of 35.5 MPM, a rapid traverse of 1.058 mm/min, max feed ratio of 0.592 mm/min, feed rate ratio of 100% and a tool change time of 15 seg.

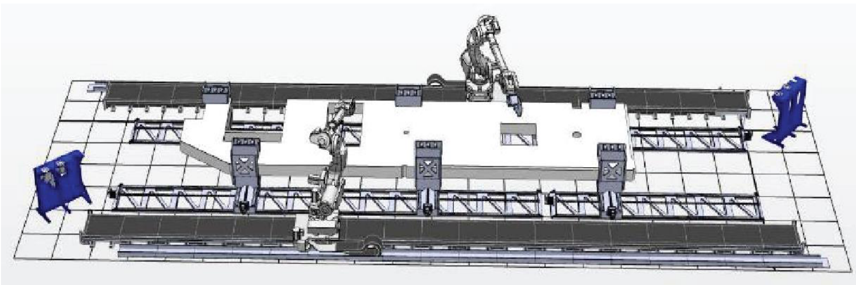

Figure 5: Robotics Simulation (taken from Villanueva et al., 2021 with permission)

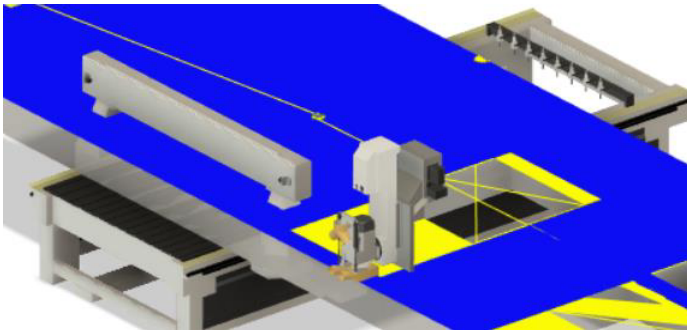

Figure 6: CNC Machining Simulation.

According to the findings of the study, the production of the CLT panel using the robotic machining cell took 18 minutes and 20 seconds (Villanueva et al., 2021), while the CNC machine took 36 minutes and 1 second to produce. The robotic machining cell is nearly twice as fast as the CNC machine, resulting in a significant difference in production time. This difference is due to the robotic machining cell's flexibility, which is programmable and adaptable, allowing it to quickly switch between different operations and make real-time adjustments. The multitasking capability of the robotic system allowed it to perform multiple operations at the same time, increasing its efficiency even further.

Assuming we have a manufacturing facility capable of producing 500 building panels per week, with a daily capacity of 100 panels. The actual demand for building panels, on the other hand, can vary greatly from day to day, so the facility must be able to adapt to changing demand. For instance, the demand for building panels is higher than expected on Monday, with a requirement of 125 panels. To meet this demand, the facility increases Monday production to 125 panels and decreases Tuesday production to 75 panels. The demand drops to 80 panels on Wednesday, so the facility adjusts its production accordingly. By the end of the week, the facility had produced 500 panels, meeting weekly demand while also being able to respond to day-to-day fluctuations in demand.

Using the information from the simulations, it is possible to produce 500 building panels per week with a daily capacity of 100 panels using the robotic machining cell. The robotic machining cell's 18 minute and 20 second production time per panel would allow the facility to produce approximately 200 panels per day, which is more than the expected daily demand of 100 panels. This provides a buffer for the facility to respond to daily fluctuations in demand. The robotic machining cell would be able to quickly adapt to the increased demand on Mondays and produce 125 panels in a single day without sacrificing panel quality. The robotic system's adaptability and flexibility allow it to quickly switch between different operations and make real-time adjustments, reducing setup time when compared to the CNC machine.

In contrast, the CNC machine, with a production time of 36 minutes per panel, would struggle to meet the increased demand on Monday. Changing tooling or setting up the machine for a new operation can be time-consuming, reducing the machine's overall flexibility and efficiency. The CNC machine's ability to respond quickly to changes in demand is limited by inflexible programming and the need for specific tooling and material options. As a result, the use of the robotic machining cell, with its quick production time and adaptability, enables the manufacturing facility to adapt to changes in demand and ensure that it can meet its production goals while remaining efficient and cost-effective. The ability to respond to changing demand is critical for any manufacturing facility's success, and the use of a robotic machining cell allows for such adaptability and efficiency.

The ability to adapt to changing demand is critical for the success of any manufacturing facility, and the use of a robotic machining cell enables such adaptability and efficiency (Javaid et al., 2022). The robotic machining cell's flexibility allows for simple process adjustments and quick adaptation to changes in product design and production sequence. This adaptability is a critical feature of a flexible manufacturing process, which is required to deal with variations in demand and product design.

As a result, the case study strongly advocates for flexibility over productivity in manufacturing processes, particularly when dealing with variations in product design and manufacturing sequence. The flexibility of the robotic machining cell over the CNC machine allows for rapid adjustment of production processes and adaptation to changes in demand and product design. The study's findings suggest that the use of robotics in manufacturing processes is an asset in the constantly changing world of industry, where the ability to respond to shifts in demand quickly and effectively is critical for success.

CONCLUSIONS

The integration of robotics into flexible manufacturing systems (FMS) in modular construction holds great promise for the future of the industry. The purpose of the paper was to present a theoretical framework for investigating the relationship between FMS and robotics in modular construction and found that the integration results in increased modular construction flexibility. The paper considered various moderator and mediator variables and concluded that a flexible manufacturing system is an essential component of Industry 4.0, with the potential to improve system performance and competitiveness.

Despite some challenges associated with the implementation of robotics in modular construction, the benefits of increased productivity, reduced dependence on labor, improved responsiveness to changing demand, and improved product quality make it a promising technology. Combining FMS with robotics in modular construction can increase production and efficiency, help to optimize operations, and reduce downtime. However, the high cost of acquiring and maintaining robots and the lack of technical expertise may limit the widespread adoption of robotics technology. To maximize the benefits of robotics integration in modular construction, it is important to carefully consider the costs and benefits and to invest in the necessary technical expertise to ensure a successful implementation.

One of the most important contributions of this study is the creation of a framework that incorporates novel mediator variables that have not previously been investigated in the context of FMS implementation. Furthermore, this study contributes to the understanding of the relationship between FMS implementation and overall manufacturing performance by emphasizing the importance of considering not only technical but also demand variability factors. While this study provides useful insights, further research is needed to understand how these mediator variables interact and how they can be effectively managed in practice.

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VISUAL MANAGEMENT IMPLEMENTATION STRATEGY: AN ANALYSIS OF DIGITAL WHITEBOARDS

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ABSTRACT

Visual Management (VM) is a communication strategy in which a visual workplace for close-range communication is created by using easy-to-understand sensory devices. It is adopted to increase process transparency and self-management capacity. VM discussions have been mostly device-centred to date, being concerned with the development of new devices, or understanding the impact of different VM attributes for different purposes. Explorations of VM as a strategy have been limited. This paper outlines the key elements of one part of an overall VM strategy, namely the implementation strategy (i.e., planning, introducing, executing, monitoring, and controlling, maintaining, and improving, and removing). It is based on an empirical study on the use of a specific type of VM device (i.e., digital whiteboards) at an infrastructure engineering design and consultancy company in the UK. The main sources of evidence were surveys with key representatives of the company and participant observation in the development and implementation of the device. Findings indicate that adopting VM through a systematic implementation strategy with coherent plans and actions is important to enable its successful application. Moreover, some future research opportunities are pointed out, such as to expand and evaluate the definitions proposed, and to test them in different contexts and device types.

KEYWORDS

Visual Management, Strategy, Digital Whiteboards, Lean, Design Management.

INTRODUCTION

Visual Management (VM) is a key element of the lean production philosophy and refers to a management strategy to increase transparency and self-management capacity at a workplace (Tezel et al. 2016). It is realised by employing VM devices that enable close-range, sensory (i.e., visual, auditory, olfactory, gustatory, and tactile) communication for different purposes.

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Transparency can be defined as the communication ability of work elements with human beings (Formoso et al. 2002). The reliance on written and text-based communication in VM should be limited (Galsworth 2005). VM devices should be easy to understand and accessible at the point of use. Information must be integrated into the workplace, increasing information availability (Greif 1991; Galsworth 1997).

VM is widely used in the implementation of lean in the Construction industry, where diverse types of devices have been used (e.g., visual boards, *kanban* cards, *andon* boards). VM discussions in construction have been driven by the lean construction community, and it is colloquially dubbed as a "lean communication system" (Tezel et al. 2016). Previous studies have proposed new VM devices as outcomes of action or design science research efforts (see for instance Brady et al. 2018), while others have assessed different types of VM devices according to functions, benefits, requirements, and purposes (see for instance Tezel and Aziz 2017; Pedó et al. 2022; Brandalise et al. 2022). Therefore, most existing VM discussions are centred around VM devices or practices. This is not surprising, as devices represent the more tangible and practical side of VM.

However, the application of VM is not limited to companies involved in the implementation of lean philosophy, as it can be employed outside a lean background. In fact, VM can be regarded, in essence, as managerial communication strategy. Therefore, research on VM from a strategic perspective at an organisational level is required.

This paper reports on initial findings of research aiming to understand the dimensions and elements of one part of an overall VM strategy, namely an effective VM implementation strategy. To the best of our knowledge, VM implementation strategy elements have not been clearly outlined in the literature to date. This is done by analysing the design, introduction, and use of a specific type of digital VM device at a large engineering design and consultancy company from the UK.

The discussions start from the VM device, and move to the company's VM strategy, indicating whether some key implementation strategy elements have been adopted. The need for a VM strategy was emphasised in a digital and dynamic context, where a more structured approach is required for the development and implementation of digital VM (e.g., digital whiteboards). Thus, the main contribution of the paper is the understanding of the key elements that need to be defined for an effective VM implementation strategy, considering the context of digital civil engineering design projects.

VISUAL MANAGEMENT

Using sensory stimuli to manage people is not new. Signals, banners, and signs have been used in armies or for managing mega projects for millennia. However, the term VM has crystallised as a concept in the last 45 years with the diffusion of the lean production philosophy in different sectors (Tezel et al. 2016). Alongside containing some more established VM devices in its toolbox, lean practitioners also recommend not copy-pasting VM devices and experimentation with VM for different contexts and information needs (Dallasega et al. 2022).

The literature has explored VM in different settings. For instance, Hirano (1995) showed how VM devices can create workplace order. Greif (1991) demonstrated that VM devices can contribute to different managerial efforts in a "visual factory". Liff and Posey (2004) extended those examples beyond factory shop floors and into other work settings such as hospitals and offices. Galsworth (2005) proposed a VM device classification system and an implementation framework. Theoretical discussions emerged from those initial, practical VM discussions. Attempts at explaining the mechanisms of VM devices through the concepts of affordances (Beynon-Davies and Lederman 2017) or boundary objects (Bell and Davison 2013) have also been explored in the literature.

In construction, Formoso et al. (2002) illustrated how VM can increase process transparency on construction sites. The adaptation of some conventional VM devices from manufacturing to construction sites has also been reported (Kemmer et al. 2006; Jang and Kim, 2007). The use of VM in construction design management has been also investigated (Tjell and Bosch-Sijtsema 2015). The functions (Tezel et al. 2016) and requirements (Pedó et al. 2022) of VM for construction have been discussed. Although some indications of VM as a management strategy can be found in previous studies (Nicolini 2007; Tjell and Bosch-Sijtsema 2015; Tezel et al. 2016; Brandalise et al. 2022), the discussions have mostly focused on VM devices and practices to date.

VM AS A STRATEGY

Beyond the development of visual devices, the literature suggests that implementing VM requires tasks such as evaluating information needs (Hirano 1995; Galsworth 2005), analysing the readiness of the work setting and elements for a VM device (Tezel et al. 2015), monitoring and evaluating the practical use of devices (Greif 1991), devising improvement and maintenance measures for the VM devices (Nicolini 2007), and capturing new VM ideas from users (Galsworth 1997; 2005). Nicolini (2007) and Brandalise et al. (2022) argued that a VM practice encompass both VM devices (the visual work of a VM practice) and the non-visual work involved in the use of the devices. A VM system is a group of visual practices working together (Brandalise et al. 2022) in order to create a visual work environment (Galsworth 2005).

Therefore, VM can be defined as a strategy for creating a "visual workplace" enabling self-management of people through VM practices (Greif 1991; Tezel et al. 2016). Being a strategy, it encompasses plans and several decisions (Galsworth 1997; 2005), such as: the purpose of the VM, the types of VM devices to be used, how people will be trained and incentivised to use the VM devices, how those devices will be created, standardised, maintained, controlled and improved, and how the devices will be linked with other production system elements and with each other.

The authors of this paper assert that decoupling VM devices and those hidden activities is necessary for a better understanding of the VM concept and successful VM applications in practice. The lack of a VM strategy, i.e., the absence of those hidden activities, may limit the effectiveness of a VM system, considering that VM will be developed as a set of random, incidental, and isolated practices which result from a trial-and-error implementation approach.

According to Chia and Holt (2009), a strategy, or a consistency of action, can also emerge from non-deliberate interventions to support immediate concerns with absence of goals specified in advance. This, for instance, can clarify aspirations, constituting a recognisable strategy with enough consistency when analysed in retrospect. A strategy does not necessarily imply something deliberately pre-thought, and positive outcomes can emerge serendipitously as a result of actions without a strong coordination effort (Chia and Holt 2009). Thus, strategies (and visions) can be a result from a combination of deliberate and emergent actions (Mintzberg, 1987).

The latter can also be developed as a consequence of bottom-up actions, mostly focused on the details, i.e., through trial-and-error, in which a pattern could be recognised as suggested by Mintzberg (1987). A strategy can also be defined as a plan, describing how goals can be achieved, or as a decision or a system of elements, as suggested by Galsworth (2005), in which the different options selected can lead to future situations, as they interact and could impact each other. A strategic plan is a formalised approach towards strategic decisions (Mintzberg, 2000) to work out the implications of a strategy (Mintzberg, 1987). In fact, different types of strategies might be required to support VM, however this paper's focus is on the implementation strategy.

Based on the literature, elements of a VM implementation strategy have been proposed, i.e., 1) planning, 2) introducing, 3) executing, 4) monitoring and controlling, 5) maintaining and improving. In the planning (1) element, decisions related to the readiness of the system need to be made, including actions such as: observe the process (Valente at al. 2019) and identify the problem or opportunities; analyse and identify user and VM requirements (Pedó et al. 2022); define visual attributes (Valente at al. 2019) by identifying patterns, coding, naming conventions or templates. The introducing (2) element of the strategy refers to training (Pikas et al. 2022) and is important to gain users' buy-in and give them autonomy to use and own the practices and devices. Implementing or executing (3) requires integration with the company system, e.g., linking with other existing VM practices and systems, as well as integrating with managerial routines (Valente at al., 2019) and identifying the types of integration and communication (Brandalise et al. 2022; Pedó et al. 2022) by pinpointing the number of users, information flow, and whether interactions are happening at the same or different location and time. By monitoring and controlling (4), the practical use of the VM devices should be assessed, as argued by Greif (1991), by adopting structured approaches for capturing users' feedback, solving problems, and managing change. Maintaining and improving (5) the device, as outlined by Nicolini (2007), was also identified as a relevant element of the strategy.

WHITEBOARDS AS VM

VM is also an approach for communication between individuals so that differing perspectives are considered towards developing shared understanding (Lindlöf 2014). (Physical) whiteboards have been shown as effective visual means of conveying concepts and ideas, facilitating discussion and collaboration among stakeholders (Shae et al., 2001), as well as establishing a common ground (Gergle et al. 2013). It is important to understand the intricate relationship of VM practices and users' cognitive processes (Valente et al. 2019), as visual aids can enhance comprehension.

In addition, in the design of digital systems, the coordination requirements are frequently ignored, such as the cognitive work of coordination and the dynamic interactions (Maguire 2019). Digital whiteboards, however, provide a flexible visual (and virtual) platform, akin to a white canvas, that enables the creation of artefacts to support remote communication and collaboration (Gumienny et al. 2013; Pikas et al. 2022). Digital whiteboards can support new routines, procedures, and activities by making it easy to pull information when required from an information field, i.e., there is an easy access to information at any time, place (or space) and device (Pikas et al. 2022).

RESEARCH METHOD

Case study was the research approach adopted in this investigation because it is suitable for studying phenomena in a real-life context, in which researchers have no control over events (Yin, 2003). The case study was part of a Knowledge Transfer Partnership (KTP) project aimed to improve collaboration between academia and industry. This project explored the integration of lean construction and digital design at an international civil engineering design and consultancy company, focused on the highways and rail sectors.

Digital whiteboards are the focus of this investigation, which were devised and disseminated through a bottom-up approach and emerged to support immediate concerns without specified goals. The case was used to recognise and refine key elements in a VM implementation strategy. Digital whiteboards were selected for this case study due to the fact that the platform presents the potential to cope with the dynamic interactions and collaboration in the context, and this is even more relevant when discussing the different elements of a VM implementation strategy. This is an ongoing research work, and more data from the company will be collected about its strategy. Moreover, there are limitations in considering data from the implementation of a single VM type (i.e., digital whiteboards).

The study had three main stages: (1) problem understanding and solution development, i.e. implementation of digital whiteboards, i.e. Miro (www.miro.com) and Mural (www.mural.co), (2) assessment of the digital whiteboard implementation through users' feedback , i.e. survey, (3) reflection upon the solution and critical analysis. The authors were directly involved in the introduction and use of the digital whiteboard. The main sources of evidence are: (1) survey with key company users (27 responses); (2) participant observation, as the researchers were involved in many applications and collected feedback throughout the implementation process; and (3) document and digital whiteboard interface analysis.

The survey had three sections (see Table 1): (1) general information; (2) user experience in using the digital whiteboards (Likert scale); and (3) challenges, benefits, and future opportunities. In the second section (2), respondents were asked to evaluate ten statements concerning the digital whiteboard characteristics on the 5-point Likert scale (strongly agree, agree, neutral, disagree, or strongly disagree). The key aspects explored are associated with the requirements for digital VM proposed by Pedó et al. (2022): simplicity, standardisation, availability, accessibility, flexibility, traceability. The challenges, benefits, comments by the respondents, and improvement opportunities captured from the survey were compared with the key implementation strategy elements proposed in this paper, supporting the refinement of the elements. This was complemented with the authors' observations of the use of the digital whiteboards. The survey responses were clustered according to the VM strategy elements, exemplifying, and expanding its definition.

Table 1: Survey Questions

Section	Questions
1	1.1 What is your role or position? 1.2 Overall, how would you rate your experience with digital whiteboards? 1.3 How would you rate the user-friendliness of digital whiteboards interface? 1.4 Why did you start using digital whiteboards? Please identify the key reason or purpose 1.5 What are the key functions of the digital whiteboard? Please select at most three options 1.6 How useful is the digital whiteboard to you considering the functions you identified? 1.7 How often do you use a digital whiteboard? 1.8 Have you had any training for using a digital whiteboard? 1.9 Who creates the digital whiteboards templates?
2	2.1 Easy and clear to use and understand the objective or function 2.2 Board templates are available and adopted 2.3 Information is standardised and consistent throughout the board 2.4 Easy to find the information because there is no excess of information 2.5 Easy to find information when required (at the right time e.g., during a meeting) 2.6 Easy to access the board because it is located in the right place, or its link is shared with the team when required 2.7 Easy to adapt the template 2.8 Easy to adapt and update the information 2.9 Easy to organise, store and backup the boards 2.10 Easy to track the information owner and changes
3	3.1 What are the perceived challenges and barriers of using digital whiteboards? 3.2 What are the perceived benefits of using digital whiteboards? 3.3 What other technologies or trends could be facilitators for the implementation and integration of digital whiteboards with existing technologies and processes? 3.4 Considering that you have used digital whiteboards extensively, how likely are you to recommend it to your friends and colleagues?

RESULTS

The starting point was a practical problem identified by the company, which had decided to implement VM and digital solutions across to increase efficiency, to deal with the challenges related to the design disciplines' fragmentation and lack of process transparency. Moreover, most design teams interactions were held in virtual environments due to the Covid-19 pandemic, affecting ways of working and collaborating. Thus, the idea of managing collaborative remote design work through digital VM was the starting point for this investigation.

The implementation of digital whiteboards was done across different sizes and types of design projects and teams, and for different functions. The digital whiteboards supported dynamic interactions, involving uncertainty, negotiation, and collaboration to establish common objectives. The key functions identified were related to planning, process mapping, and brainstorming, representing 68% of the survey responses (Figure 1 shows the interface of two VM practices using digital whiteboards as the medium to implement it). These were followed by continuous improvement and lessons learnt, representing 12% of the responses. The key purpose for starting the digital whiteboards adoption was to aid collaboration and support continuous improvement (60% of the responses), followed by knowledge management and sharing information. The previous knowledge on how to use, the top-down support, and the platform availability and easiness of use also influenced its implementation. Thus, the whiteboard dissemination for other uses was also facilitated due to the fact that the teams became familiar with the whiteboard interface and its functionalities.

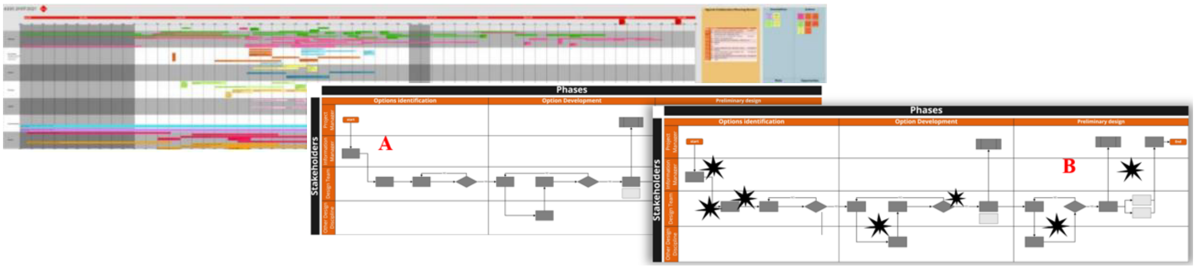

Figure 1: Digital Whiteboard Interface for 'Planning' and 'Process Mapping' Applications.

Most participants (68%) had not had any training on digital whiteboards. Nevertheless, the majority (78%) answered 'great' or 'excellent' for the user-friendliness of the digital whiteboards interface. In addition, 82% of participants answered 'great' and 'excellent' for their experience in using digital whiteboards, and the majority (85%) answered 'useful' and 'extremely useful' for the usefulness of the platform related to the key functions identified. Thus, 96% would likely or very likely recommend the platform to colleagues.

Most of the users can be described as BIM or digital managers and coordinators (30%), technical directors (22%), BIM or digital leads (19%), designers or engineers (11%), and others (18%), such as GIS coordinators or leads. There was daily and weekly frequency of use (17 responses out of 27), and the templates were usually developed by the continuous improvement practitioner or digital / BIM leads, not by the users.

Considering the user's experience in adopting the digital whiteboards for different functions, the comprehensibility, accessibility (right place), availability (right time) and information flexibility aspects were outlined as positive characteristics of a digital whiteboard (see Figure 2). The majority of the survey participants answered 'agree' or 'strongly agree' to 'easy and clear to use and understand the objective or function' (85.2%), 'easy to find information when required (at the right time e.g. during a meeting)' (70.4%), 'easy to access the board because it is located in the right place, or its link is shared with the team when required' (92.6%), and 'easy to adapt and update the information' (81.5%). In contrast, traceability and template flexibility were highlighted as negative or neutral aspects, considering most of the participants answered 'disagree' or 'neutral' to 'easy to adapt the template' (59.3%), 'easy to track the information owner and changes' (59.2%).

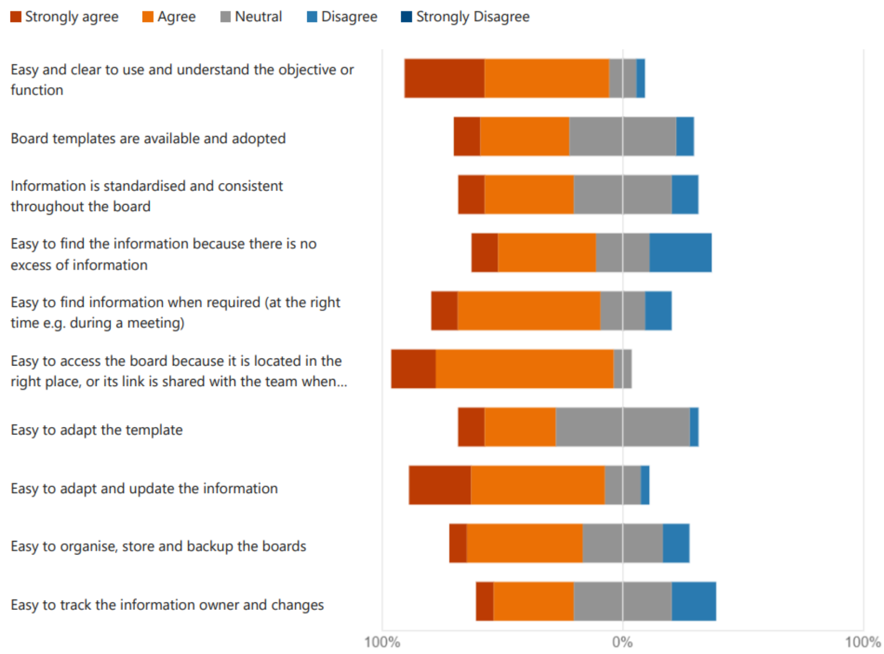

Figure 2: Users' Experience with Digital Whiteboards.

DISCUSSION

Table 2 presents the key VM implementation strategy elements (i.e., planning, introducing, executing, monitoring, and controlling, maintaining, and improving), based on the literature review, and refined considering the survey results and participant observations, i.e., the researchers' insights and observations as a source of evidence. The paper suggests that the VM implementation strategy elements proposed follow the plan definition or strategic planning, as suggested by Mintzberg (2000), however, they impact each other and some of the definitions could be analysed and interpreted through the decision lenses, in which there is a system of elements to consider as argued by Galsworth (2005), e.g., whether manual, digital or hybrid VM should be adopted or whether it should be implemented in production, administrative or management activities.

The 'planning' element relates to analysing the readiness of the work setting and elements for a VM device implementation (Tezel et al. 2015). It was emphasised by the challenges faced by the team members associated with the early identification of technical and system requirements, as well as with the early identification of the visual attributes. The team highlighted the need to have a plan regarding the correct number of licences (and financial implications), and permission in place before using the platform, as the lack of a full licence could restrict the adoption of some functionality. Setting up the boards' access and restrictions in early stages of the implementation was also identified as a key aspect, as this could avoid issues related to the security of information. The assessment of the need, process, problem, and opportunities is also a relevant aspect of the planning as identified by one of the users, avoiding the introduction of unnecessary boards. This is also related to an early identification and analysis of the VM application purpose and requirements. The definition and agreement on the visual device attributes (Valente et al. 2019), such as content and format, as well as identifying and prioritising relevant information (Hirano 1995; Galsworth 2005) was outlined as fundamental when working with a digital whiteboard, as the excess of information or space to work could be overwhelming for its users and it could become very disorganised. In addition, a clear and disciplined way of using such dynamic devices is a must have and it should be agreed in the planning stage (with room for improvement if required). It was suggested by one of the survey respondents that having a governance process in place could provide support in overcoming those challenges by consolidating and standardising the digital whiteboard management process. One of the participants also identified the time required to develop [and maintain] the board as a challenge, which underlines the need to consider ideating, prototyping, evaluating, and selecting appropriate solutions when possible.

Table 2: VM Implementation Strategy Elements Refined.

VM strategy elements	Definition	Output	Source
Planning	Analyse the readiness of the system and users, by considering its processes, VM purpose, user and system requirements, problems, and opportunities (e.g., emerging technologies), visual and non-visual attributes, and prototype possible solutions.	Planning strategy including cost and implementation plan	Literature review and researchers' insights/observati on
Introducin g	Train users, provide guidance, facilitate initial applications, and handover to them.	Training and ownership-building plan	Literature review and researchers' insights/observati on
Executing	Integrate in the company system by linking with existing VM practices and systems, as well as integrating with managerial routines, and communication and collaboration practices.	Execution plan	Literature review and researchers' insights/observati on
Monitoring & controlling	Monitor and evaluate the practical use of VM devices, outline certain criteria for control, capturing the users' feedback through standard approaches defined by the company.	Evaluation plan	Literature review and researchers' insights/observati on
Maintainin g & improving	Identify key elements of the device or practice that needs to be adjusted or improved.	Maintenance and Continuous Improvement plan	Literature review and researchers' insights/observati on
Removing	Identify practices that need to be removed from the system due to different reasons	Exit strategy	Researchers' insights/observati on

The 'introducing' element of the VM implementation strategy refers to the effort required prior to the device implementation in order to ensure the users understand its purpose and how it works. It is not only related to training, but also associated with the initial support with its implementation aspects (Pikas et al. 2022) and facilitation required until the users feel confident in using and owning the device, when it can be handed over to the users. As stated by one of the respondents: 'willingness to adopt new digital tools sometimes limits people or their awareness. Sometimes there is a strong resistance from people to change as '[...] they are not prepared to adapt, change or flex to a situation'. This highlights the cultural challenges and emphasises the need for change management, including training, guidance, and ownership-building activities, before the platform implementation. Also, updates to the platform interface or functionality, as well as in the standards, might only be understood by the users with guidance. This would increase their awareness of the platform interface and its functionalities, but also the VM relevance and impact in their own tasks. Ensuring all staff know how to use the platform properly and acquire experience on it to gain the maximum benefit is required.

'Executing' focuses on the integration of the VM practice into the company systems by linking it with existing VM practices and the managerial routines, as suggested by Valente et al. (2019). Identifying the types of communication (i.e. face-to-face, asynchronous distributed, asynchronous, synchronous distributed, and hybrid synchronous distributed & face-to-face), as well as the number of users and the type of interaction (e.g. one to one or many to one, as suggested by Brandalise at al. 2022) is essential to define the level of digitalisation of a device, e.g. if the device should be manual, digital or hybrid in order to meet the users' requirements. The digital whiteboards were often implemented considering an asynchronous distributed or synchronous distributed collaboration, as well as a high number of users. However, the digital whiteboard adoption through face-to-face or hybrid synchronous distributed and face-to-face approaches is still considered a challenge by the company members due to the staff lack of previous experience and knowledge on how to use it.

The integration of the digital whiteboard into the company processes was facilitated by its user-friendly interface (i.e., clear to use and understand its objective), easy access (stored in the cloud and accessible via website without the need to download apps), and all information being available in one place. In addition, the board templates and information flexibility encouraged its application for different functions, e.g., planning, process mapping or brainstorming. They enhanced collaboration through an efficient connection between the users, by allowing them to access the space and interact to each other in a similar way they would interact face-to-face.

The 'monitoring & controlling' element emerged as a relevant aspect of a VM implementation strategy and it was emphasised by the digital whiteboards due to their flexible and dynamic character. Information management was a challenge identified by the company members, as information could be easily changed without any notification, requiring even more coordination and structure. Regular backups and version control were also found to be essential for the monitoring and controlling process, even this could be considered challenging. A better integration of the digital whiteboard with other existing platforms commonly adopted by the company (such as Task Planner in Microsoft Teams, SharePoint, the scheduling software, or Excel) was suggested as an improvement by the users to support the control activities, as tracking of historical tasks was still considered a challenge. Thus, great benefits could be achieved through a better integration across other software already adopted by the company. As future opportunities, the teams also identified programming, e.g., to automate tasks, as a high-potential aspect that could support this integration.

On the other hand, the users also stated that information was centralised, acting like a source of truth, and avoiding having multiple revisions of documents due to the collaborative nature of the work. Digital whiteboards allow everyone to use the same board at the same time remotely, in a virtual space, and make changes simultaneously, highlighting the importance of the controlling and monitoring elements of a VM implementation strategy. In addition to this, capturing the users' feedback through standard and regular approaches defined by the company, e.g., a survey or the method of plus and delta, or management's observation were also identified as good practices to monitor the current implementation, as well as to identify improvement opportunities and guide future applications. In short, how the users interact with a VM device, and whether they use some or all parts of it as intended should be monitored and controlled, as argued by Greif (1991), with predefined mechanisms. This also includes adopting certain criteria and indicators for the control.

The 'maintaining & improving' element is related to identifying key elements of the device or practice that needs to be adjusted or improved, as well as to creating a maintenance and improvement plan to support those changes, corroborating with Nicolini's (2007) suggestion for devising improvement and maintenance measures. Due to the flexibility and collaborative nature of the whiteboards, it is easy for users to diverge from standard templates, adapting existing templates or using other areas of the boards, which can make it difficult to easily identify relevant information, as stated by one of the respondents. As argued by another team member, over a period of time, the boards become a massive information repository as it is very easy to add information by different people. The amount of time required to update the boards could also become a challenge. Thus, keeping the board structured and maintained is even more relevant, highlighting the importance of the board owner's role to do the housekeeping from time to time. Regular lessons learned shared on its adoption were observed by the researchers as a best practice to support continuous improvement and capture new VM ideas of people, as suggested by Galsworth (1997; 2005). To this end, VM devices can be subject to the Plan-Do-Check-Act (PDCA) continuous improvement cycle. Idea capturing activities, such as workshops, brainstorming and benchmarking sessions, suggestion boxes/boards, can also be adopted.

The ‘removing’ element is about recognising when a VM practice is not achieving the desired outputs and removing it from the system. This could happen due to different reasons, e.g., when the practices are obsolete or not aligned with their purpose, when the context changes, or due to the end of a project or activity. Without harming the users’ view of the strategy and affecting their work, a VM device exit plan should be in place. This includes a communication plan with the users for the reasons of removal, the timeframe for removal, what is going to happen to the information recorded on the VM device to be removed, alternative information channels to substitute the VM device to be removed, new arrangements between the management systems and routines and the VM device to be removed, and future actions in line with the lessons learnt after the removal.

An emergent expansion of the VM device application, through trial-and-error, was noted; people started to adopt the digital whiteboards for different functions and purposes, as the teams became familiar with the whiteboard interface and its functionalities, facilitating its dissemination for other uses. In order to support spontaneous innovations, like the digital whiteboards, an emergent and flexible strategy should be considered where only a few elements could be implemented, e.g., monitoring & controlling, maintaining & improving, and removing. However, as soon as a spontaneous innovation is recognised, the other elements of the VM implementation strategy could also be adopted (such as planning, introducing, and executing), and a deliberate or planned strategy could be devised. This corresponds to the bottom-up approach to VM, which often yields to effective VM solutions for people’s information needs, if managed properly (Galsworth 2005).

CONCLUSIONS

VM is often perceived as an intuitive concept executed over sensory devices. This is a limited view to VM, and partly due to the seemingly effortless effectiveness of sensory communication. However, to be able to implement VM as a strategy for creating a visual workplace catering to different contexts and needs, coherent plans and decisions should be in place. These include the VM implementation strategy elements which were explored in this paper at an engineering design organisation as a case. The findings showed the need to understand and address the strategy elements for a successful VM implementation, the absence or deficiencies of which could lead to various challenges and questions during the implementation.

Digital whiteboards are expanding the scope of VM application and the need for a VM implementation strategy has been emphasised to cope with the dynamic interactions in the analysed context. In practice, some of the strategy elements (e.g., colour scheme to be used in VM devices as part of defining visual attributes during the planning) could be adopted as a standard for many VM devices within an organisation. Some of the VM strategy elements still need to be reviewed and tailored for each VM device or practice separately (e.g., integrating with company systems and managerial routines during the executing). The proposed VM strategy elements are initial and by no means definitive. Future research can look at expanding and evaluating definitions and implementation of the strategy elements for different contexts (e.g., construction sites, facilities operations), for different VM purposes (e.g., information sharing, controlling, and limiting human actions), and for different VM device types (i.e., manual, digital or hybrid). The VM strategy elements can be further investigated for the top-down and bottom-up implementation modes. The strategy definitions can also be expanded and broken down to tactical level practices or other choice elements.

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WORKSHOP FOR LEARNING VISUAL MANAGEMENT IN JAPAN: A REPORT

Koichi Murata[1]

ABSTRACT

This paper provides a report regarding a visual management workshop conducted for business persons in Japan from September to December 2022. The aim of the workshop was to aid the participants in solving their problems via the visual management theory developed.

Based on literature review, recent research trends pertaining to visual management show that the concept has disseminated widely. Nonetheless, the presence of various related studies with different contexts suggests the insufficient understanding of the concept. Hence, academics must endeavour to explain the details of visual management in a unified manner such that it can be applied more effectively. The purpose of this study is to address such issues based on the workshop above, as well as to describe and discuss the state of the workshop.

For the study, the plan–do–check–action (PDCA) cycle, which is a well-established problem-solving process used in various fields, is applied. This paper summarises the workshop based on four categories: planning, implementation, evaluation, and discussion (based on the PDCA cycle). Data obtained from the workshop include relevant materials, observations from the workshop, as well as interviews with the participants.

The conclusions obtained are as follows: First, participants from various industries with their respective issues can participate in the workshop. Second, the outcome of the workshop, i.e., the understanding that visual management connects people, instead of being a tool, is recognised by all the participants.

KEYWORDS

Visual management, lean education, workshop, PDCA cycle, Japan context.

INTRODUCTION

Visual management is a core lean management methodology used to increase operational transparency. People's lives and work involve various operations. A public transportation system is an ensemble of operations that allow people and vehicles such as cars and trains to move at comfortable speeds. The function that provides alerts regarding abnormalities on the transportation system is equipped with signals that protect pedestrians from iron lumps. Hence, visual management provides transparency to various operations. In addition, in the digital age, smartphones are used to publicise one's interests and behaviours. In addition, digital platform providers that offer these services are equally interested in such information as users and are striving to improve service quality as well as develop new products. Clearly, visual management demanded in many situations.

To understand visual management more comprehensively, the concept must be theorised and disseminated widely to society. Various studies have been conducted regarding the former. Tezel et al. (2015) and Valente et al. (2019) presented various examples and discussed their

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common denominators. Similarly, Murata et al. (2010) proposed a horizontal expansion system via a detailed case analysis. Additionally, studies have been performed to interpret cases using affordance theory (Beynon-Davies et al., 2017), of which the latter will likely be included in lean management courses in universities. Furthermore, visual management workshops, consulting services, and books are available.

The purpose of this paper is to provide a report on the workshop, "Tsudanuma Mieruka Juku", which was conducted from September to December 2022 (Herein, "Tsudanuma" is the name of the area, "Miekaka" means visual management, and "Juku" means workshop in Japanese). The laboratory associated with the workshop, in which lean management is investigated, is where visual management workshops for business persons are designed and operated. The purpose of the workshop is to contribute to society by applying the results obtained from a university to the local community. The target is business persons in the area where the university is located. The main features of this workshop are as follows: First, the participants are not specific to one industry or company. The organisers of the workshop attempt to embody the fact that the concept of visual management is of widespread social interest. Second, a particular perspective management theory is used (Murata, 2021). The program is structured around one theory for diverse participants, which is the first feature. Although most of the participants are aware of the practical use of visual management, the robustness of the concept is tested in the workshop. This paper presents the results of this workshop to provide a more comprehensive understanding.

In the next section, recent trends in studies pertaining to visual management as well as the visual management theory used in this workshop are expounded. Section 3 describes the research method, and Section 4 provides the results obtained. Section 5 presents the overall overview.

LITERATURE REVIEW

RECENT VISUAL MANAGEMENT STUDY

Recent studies pertaining to visual management can be classified into four categories: 1) Description and consideration of usage situations; 2) evaluation and use of toolboxes; 3) effect of usage history; and 4) integration with other theories.

The first is the description and consideration of the usage scene of visual management. Some papers describe several cases comprehensively, where the role of visual management in each case and barriers to the introduction are expounded (Kurpjuweit et al., 2019; Tezel et al., 2017; Tjell et al., 2015).

The second is the evaluation and use of toolboxes for visual management. Tools for visual management abound. Owing to the progress in digital technology, visual management continues to evolve. Hence, studies related to each tool have been performed. Singh et al. (2021) attempted to determine the tool (among 12 tools) that was the most applicable. Bateman et al. (2016) focused exclusively on communications boards and conducted two years of utility survey.

The third is the effect of usage history, which pertains particularly to nurses. Williamsson et al. (2019) classifies users into nondaily, start, and daily users, and measured their usage effects. Dalain (2020) categorised the history of VM usage into less than 5 years, 5-10 years, 10-15 years, and 15+ years, and investigated the effect of tool usage on work performance.

The fourth is integration with other management concepts, which aims to determine the applicability of visual management by considering its integration with other concepts. According to Brady et al. (2018), visual management may effectively enhance one's ability to execute plans in project management. Additionally, the relationship between performance management and continuous improvement (Eaidgah et al, 2016) as well as the contribution of visual management to change management (Eriksson et al, 2018) were considered.

Based on the studies above, the following two conclusion can be inferred.

First, the concept of visual management is pervasive. The fact that related studies were conducted from various perspectives indicates the abundance of cases in this field. This is also supported by the fact that visual management is a management concept in which the useful tools have not been clarified.

Second, the understanding of visual management is insufficient. As observed by Williamsson et al. (2019) and Dalain (2020), different users perform differently at work, which suggests the nonexistence of unified understanding regarding this concept. This is partly due to the complexity and ambiguity of the concept.

Based on the above, academics must endeavour to explain the concept of visual management in a unified manner such that it can be used more effectively. It means that they make an effort to discuss how to disseminate and teach visual management.

Framework Learned in the Workshop

The theory used in the workshop, which is used to explain visual management in a unified manner, is based on Murata (2021). It is developed based on control theory and describes the internal structure of visual management. Based on this theory, the following three basic principles are provided in this workshop:

- Principle 1: Someone and someone else
- Principle 2: Why, what, how
- Principle 3: Sometimes I

Principle 1: Someone and Someone Else

Visual management is a tool that connects a person with another. When developing this tool, one must first ensure that a person is connected to another. Additionally, customers' requirements must be considered when developing products and services to ensure that they benefit from visual management. Henderson (1991) noted visual communication involves *boundary object*. Star et al. (1989) described that *boundary objects* are *both adaptable to different viewpoints and robust enough to maintain identity across them*. Also, good visual management is a *conversation for action* (Flores, 2012) that needs no interpretation and provokes desired behaviour. "Someone and someone else" imply a person and another person; however, it can also imply a human and a machine or a machine and another machine. The two connected entities have their own roles. One is the information sender and the other is the information receiver. However, the roles are not fixed. Similar to the two sides of a coin, the roles of each may be exchanged. Although two entities may know each other well, they must be re-understood.

Principle 2: Why, What, How?

This principle is applied to develop three elements, "reactions", "message", and "transmission" in a tool for practical visual management. It comprises the following three questions. They do not aim at promoting visual management. They just think about a component of a visual tool:

- Why do you see?
- What do you see?
- How do you see?

The first question reveals the reason for developing the tool, i.e., the necessity for visual management. In this regard, one considers the type of change that can be expected from the newly created interaction via visual management. After visual management is introduced, it appears that the type of change is "reactions" from a person, which must be investigated comprehensively. For the second and third questions, the specifications of the tools must be considered. The second question clarifies the "message", which is typically hidden prior to the development of the tool. However, its connection must be clarified. In the case of the pedestrian traffic light development in Figure 1, a “message” developed from the second question is about whether pedestrians should or should not cross. The third question clarifies "transmission". How to convey a message developed? There are many types of a traffic light in the world. Not only the physical method, but also the timing, environment, amount of information, combination of various methods, and the degree to which the opponent resonates differ.

Principle 3: Sometimes I

Principles 1 and 2 pertain to visual management tools and their users, i.e., visual management. Principle 3 is the designers' perspective of visual management. The manufacturer of a product or service contributes significantly to purchase decisions. What type of life do designers lead? Understanding the thoughts involved in developing visual management will promote its use. When the pedestrian traffic light is red, Japanese people wait until it turns green. But the British will cross if there is no car. Let's assume that the designer has extensive experience in developing pedestrian traffic lights. A designer's daily life and life influence the development of visual management.

Among the three principles, Principles 1 and 3 are related to people, whereas Principle 2 is associated with tools. Since the former two principles involve people, they provide a description of management based on people. Additionally, although Principles 1 and 3 pertain to meta-level knowledge and are used for designing visual management, the items to visualise in any area are not specified. Hence, they are general principles that are applicable to various visualisation targets.

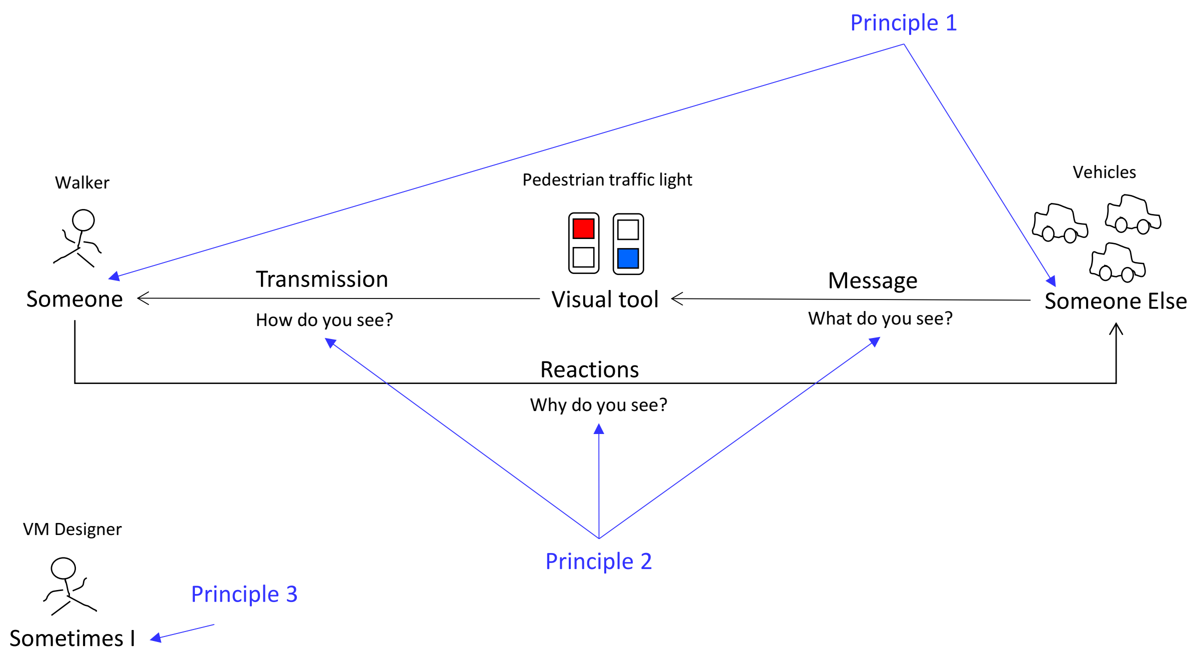

Figure 1: An example of pedestrian traffic light by the theory used in the workshop

RESEARCH METHOD

This study was performed based on the plan–do–check–action (PDCA) cycle, which is a typically used problem-solving method in quality control. In fact, it is well established and applicable to many areas other than quality control (Chakraborty, 2016; Kholif et al., 2018; Pietrzak et al., 2015; Realyvásquez-Vargas et al., 2018). In the PDCA cycle, continuous learning can be expected by continuously rotating the processes involved. The planning, implementation, evaluation, and discussion of the workshop are discussed herein based on the four processes of the PDCA cycle.

Workshop Planning (Step 1-Plan)

In this step, the organiser plans the workshop. This paper describes the purpose, expected results, implementation period, program, etc. pertaining to the proposal prepared for budget acquisition, as well as provides an overview of the workshop. Consequently, the configurations and conditions in which visual management is learned can be understood.

Workshop Implementation and Evaluation (Step 2-Do and Check)

This step describes the implementation and evaluation of the workshop. The current author is the main instructor of the workshop. The contents presented herein are objective information obtained directly from lectures.

The data obtained from the workshop include the profiles of the participants, the participation status in the workshop, as well as the themes of each participant and their outlines.

Additionally, data are obtained from evaluating the workshop from the perspectives of the participants. This is performed after the workshop is completed. The evaluation method is a questionnaire, in which multiple questions regarding the workshop process as well as visual management theory are posed, and answers are obtained in a multiple-choice format. In addition, the participants are interviewed to qualitatively obtain their impressions of the workshop. Thus, knowledge will be gained by observing the participants and exchanging opinions with them during the workshop.

Discussion of the Workshop (Step 3-Action)

This step considers the data obtained in Steps 1 and 2. Additionally, future issues identified from the workshop are considered and discussed based on visual management theory described in Section 2.

RESULTS

Workshop Planning (Outcome of Step 1)

According to the workshop proposal, the workshop will provide opportunities to learn visual management theory via a mini-lecture and an informal practice for business persons (5 years or more of working experience) who will lead their company in the future. One of the purposes of this workshop is to develop the ability to identify problems using management resources and to foster communication with colleagues for solving them.

The expected results are as follows: The first is to provide the understanding that visual management is not merely a tool, but represents human and technical ability to identify the essence of a matter. The second is to achieve positive awareness in terms of the thought process and attitudes toward daily work and foster the Kaizen mindset. The workshop comprises four sessions, each of which is conducted once a month from September to December 2022. The first three are online workshop and the final one is a face-to-face workshop. The topic of each workshop is as follows: Part 1 - Basic theory of visual management: three principles of design; Part 2 - Visual management strategy in the era for digital transformation: Digital visual management; Part 3 - Nishida's philosophy and the future of visual management: Feeling and one step mind; Part 4 - Final presentation by all participants.

In addition, individual meetings are conducted prior to each session.

IMPLEMENTATION AND EVALUATION OF WORKSHOPS (OUTCOMES OF STEP 2)

Implementation of the Workshop

Initially, six people applied for the workshop before it was conducted, and all of them participated until the final presentation. The affiliations of the participants were as follows: two persons in the manufacturing industry, a person in the retail industry, a person in the real estate industry, a person in tax accounting, and a person in the public sector. Four males and two females participated in the workshop, and their ages ranged from 20 to 50. The theme of each participant was as follows:

Participant 1: Continuous management for several visual displays

In this theme, the participant considers the life cycle management of several visual displays used for plant operation. In particular, the incorporation of display maintenance into normal operations is considered.

Participant 2: Innovation in the manner by which meetings are conducted

In this theme, the participant considers the manner by which a meeting is to proceed. After solving the problems in meetings with multiple participants, the participant considers the manner by which a meeting is to be conducted with minimal loss. This theme pertains to communication when a task is performed.

Participant 3: Visual management for connecting operators and users

In this theme, the participant identifies a method to improve the motivation of operators in a factory, which involves consideration into the requirements of product users. In particular, the participant uses an example of a girlfriend who prepares bento (lunch box) for her boyfriend as a metaphor.

Participant 4: Preparing posters for tax accounting office

In this theme, advertising strategies for attracting customers in the area where the office is located are examined. In particular, an appropriate poster is created.

Participant 5: Attempt to use visual management theory via analysis

This participant did not address the subject of his own work. Instead, the participant analysed the theory introduced in the workshop and attempted to understand and use the theory.

Participant 6: Management and operation method for rental buildings using a visual management design framework

In this theme, the efficiency of daily building management is analysed. Timely information sharing and reduction in personnel costs by adopting digital technology are proposed. The participant attempted to understand the theory more intensively based on the communication between a husband and a wife.

Evaluation of the Workshop

Table 1 shows the responses to the questionnaire provided to the participants after the workshop ended. In addition, descriptions provided by the participants regarding their overall impression of the workshop are provided herein.

Table 1: Questionnaire results

Questions	1	2	3	4	5
Q1 How difficult was the visual management theory? (1low ⇔ 5 high)	-	-	1	3	2
Q2 How useful was the visual management theory? (1low ⇔ 5 high)	-	-	1	3	2

Descriptions by participants

Participant 1:

When I first viewed the theory, I thought that it was extremely philosophical. It took me a while to understand it; however, after I understood it, I was able to apply it to my theme to obtain new solutions. We will focus on introducing it in the future.

Participant 2:

I appreciated the opportunity to communicate with the teachers individually.

Participant 3:

The more I thought about the theory, the more difficult it appeared to me. However, I gained some new knowledge, which I appreciated very much.

Participant 4:

I would appreciate more practical cases.

Participant 5:

I would like to learn from the textbooks that I have received. Unfortunately, it was difficult to understand the connection between philosophical and technical topics. The cases provided were few, and I did not know how to proceed.

Participant 6:

In my opinion, working professional will benefit from the lectures, even if they are longer in duration.

DISCUSSION (OUTCOMES OF STEP 3)

As mentioned in Section 2, academics should endeavour to explain visual management in a unified manner such that it can be applied more effectively. In this regard, the following aspects should be considered:

Versatility of the visual management theory provided

The participants participated in all workshops and provided a final presentation. The industries represented by the participants were manufacturing, retail, real estate, tax accounting, and public sectors. The themes were life cycle management for visual displays, meeting management, advertisement, supply chain management, and building management. Hence, the theory provided in the workshop presents a certain degree of versatility.

Trends in participants' understanding of the theory provided

From the answers to Question 1, many participants seemed to find this theory difficult. An analysis of the materials presented by the participants showed a tendency to focus on Principle 2 of the theory. This suggests that visual management is primarily recognised as a tool. Based on Principle 2, designing a tool is the final output of visual management. However, the aim of visual management design is to connect people. Principles 1 and 3 involve processes that deepen the understanding of users and designers. The essence of the theory explained in the workshop is that Principles 1 and 3 are prioritised before and after the realisation of Principle 2; hence, Principle 2 is used to design a visual tool. Many participants successfully applied Principles 1 and 3, although at different degrees.

Undesired effects of conceptual learning and the countermeasures

Based on the comments provided in the questionnaire, participant 5's opinion looks like negative. This participant requested the introduction of actual examples. However, after visual management theory was explained in the first session, the lecturer implemented to illustrate actual examples in a question-and-answers session during the lecture as well as through individual online meetings. The second and third sessions were delivered while considering technical and human aspects, respectively, of recent visual management. Instead of providing the necessary knowledge for designing these tools directly, recent progress and thought processes related to visual management were introduced. The planned intentions of the workshop deviated slightly from the requests of the participants. The author of this paper was workshop instructor and researcher. However, the merit of this dual role was not utilized. If the former communicated this problem to the latter and the plan was revised during the workshop, the resolution of the deviation might have enhanced the participant's understanding of the theory.

From the answer to Question 2, participants generally find this theory useful. Participants 1 and 3 expressed difficulties in understanding the provided theory; however, they gained new awareness in the process. A new concept is generally difficult to completely understand; consequently, a new thought process emerges. The participants' comments suggest that their impression toward this theory is positive.

CONCLUDING REMARKS

A report regarding a visual management workshop conducted in Japan was provided herein. In particular, the workshop was intended for business persons within a university area. The lecturer who participated in the workshop is the author of this paper. Information obtained from the workshop were organised, and the participants' understanding of the visual management theory provided were considered.

In lean management, visual management is a widely known methodology. However, to use it effectively, academics must endeavour to explain it in a unified manner. This was addressed in the workshop, and the results obtained were analysed.

Visual management is introduced to connect people and is not merely a tool. The workshop allowed the participants to understand the concept together. The results showed that they successfully acquired a unified understanding of visual management.

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DEVELOPING AND TESTING COMPUTER- AND VIRTUAL REALITY-BASED TARGET VALUE DESIGN SIMULATIONS

Suryeon Kim[1], Zofia Rybkowski[2], and H. David Jeong[3]

ABSTRACT

Knowledge of fundamental lean construction principles and tools is often imparted through the physical playing of serious games and simulations. However, globalization and the emergence of the recent pandemic have created increasing demands for scalability, as well as for diverse player usability and remote implementation of the games. That said, there are challenges associated with transforming existing lean simulations to technology-oriented modes, such as computer- and VR-based formats. For example, while the potential of using advanced formats is promising, it is unclear if these versions offer an equivalent level of learning effectiveness as in-person play. This research reports on the development and testing of different forms of the Marshmallow Target Value Design (TVD) Simulation, including computer- and VR-based formats. Researchers administered and assessed post-simulation questionnaires, and the moderator effect of perceived usability was determined and analyzed. Results show that the computer-based format was more effective than the physical-based format for some TVD principles and that the VR-based format was more effective than the physical-based Marshmallow TVD Simulation for most TVD principles. For the computer-based format, usability moderated learning effectiveness. These results indicate that when developing a computer-based simulation, the usability of the simulation must be considered to ensure maximum effectiveness.

KEYWORDS

Serious games, simulations, target value delivery (TVD), computer-based simulation, VR-based simulation.

INTRODUCTION

Serious games and simulations, primarily designed for educational purposes other than entertainment, play a vital role in the testing and teaching of lean design and construction principles and methods (Bhatnagar et al., 2022; Tsao & Howell, 2015). They impart confidence about lean principles, and by creating a highly immersive environment, they make learning enjoyable. This pedagogical approach promotes engagement and creates links to applicability of instructional content by bridging the knowledge gap between theory and applications (De Freitas & Oliver, 2006; De Freitas & Levene, 2004). Serious games and simulations have been shown to students and practitioners to be effective in imparting lean construction principles

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and tools—as well as in creating buy-in with participants. In fact the expansion of adoption of lean construction is likely responsible, at least in part, to the illustrative impact of serious games in both academia and industry (Bhatnagar et al., 2022).

Serious games and simulations have been—and still are—typically administered in a physical format, in which in-person interactions, active task involvement, and hands-on experience are maximized; these qualities been shown to improve learning (Rybkowski et al., 2021). However, as adoption of lean construction has expanded, projects have also become increasingly globalized to include multi-cultural stakeholders; pedagogical environments have become diverse and advanced, leading to the need to enhance scalability of serious gaming. The emergence of the global COVID-19 pandemic also heightened the demand to take gaming into digitized and remote formats (Rybkowski et al., 2021). Virtual formats offer the potential to accommodate varied geographical regions with greater accessibility. They also enable users to become highly immersed in the educational process (Schroeder et al., 2020).

While there are growing efforts to transform lean serious games and simulations into advanced learning environments, such as computer- and virtual reality (VR)-based formats, several areas must still be addressed. Firstly, there is a need to know whether different learning environments can promote the same amount of knowledge retention and learning effectiveness. Although there is a prevalent belief that learning with serious games and simulations offers similar cognitive effectiveness, differences in format may be significant in their capacity to provide effective learning (Ypsilanti et al., 2014). Furthermore some researchers have concluded that computer-based serious games and simulations do not always offer a positive impact on learning (Erhel & Jamet, 2013; Liu et al., 2020). Second, computer- and VR-based formats require a certain level of technological familiarity which significantly influences users' attitudes toward active involvement (Davis, 1989; Idris et al., 2015). The success of learning lies in actual involvement in the process, and users' negative attitudes may hinder them from learning (Tsai et al., 2015; Ypsilanti et al., 2014). To systematically investigate those areas, the development and testing of serious games and simulations in different formats are needed.

This research aims to develop and systematically test two formats of simulations: a computer (keyboard)-based Marshmallow TVD Simulation and VR (headset)-based Marshmallow TVD Simulation, which mimic the physical Marshmallow TVD Simulation's overall concept, framework, and rules. Two valid research questions, which will contribute to the current body of knowledge, were explored: (1) Are there differences in knowledge retention for physical- vs. computer- vs. VR-based formats? and (2) What is the effect of perceived usefulness and usability on knowledge retention for computer- and VR-based formats?

BACKGROUND

MARSHMALLOW TVD SIMULATION

Target Value Design (TVD) is one of the most effective lean processes that adapt the target costing concept to the peculiarity of the construction industry (Zimina et al., 2012; Engebø et al., 2021; Jacob et al., 2021). TVD is a management practice that aims to deliver a project within a specified allowable budget by promoting innovation throughout the project life cycle, increasing value and eliminating waste, and continuously improving a project's design in order to reach desired goals, thereby satisfying the client's values (Alves et al., 2017; Rybkowski et al., 2016; Zimina et al., 2012). Target Value Design is an adaptation of Target Costing for construction project delivery (Ballard, 2011; Zimina et al., 2012), constituting the design phase of Target Value Delivery (Hill et al., 2016).

The Marshmallow TVD Simulation is one of the full-blown lean simulations designed for practicing the TVD process. It simplifies traditional and TVD processes so participants can intellectually grasp the TVD framework (Rybkowski et al., 2016). The simulation consists of two rounds. In each round, participants build a tower that can hold a marshmallow at the top with supplied materials (e.g., drinking straws, uncooked spaghetti noodles, coffee stirrers, bamboo sticks, masking tape, and a marshmallow). The tower should be at least 60 cm (approximately 2 feet) tall and free-standing (i.e. not taped to the table). During Round I, participants build a tower without awareness of the unit cost of each material. After the first round is finished (within approximately 20 minutes), they count and report the unit amount of each material they chose to use to build their tower so that a typical Market Cost (an average of all towers) is established. Target Cost is then set to be 20% lower than the Market Cost, and an even lower “stretch goal” (Allowable Cost) is declared by each team. During Round II, participants again build a tower, but this time within the Target Cost (and potentially even their individually declared Allowable Cost). At the start of this round, they are given information about the unit cost of each material Amounts reached per team are collected on a spreadsheet and projected on a wall for all to see and discuss following play (Munankami, 2012; Rybkowski et al., 2016).

The Marshmallow TVD Simulation is a good candidate to be developed and tested in various modes, including physical-, computer-, and VR-based formats. Firstly, it requires a sense of spatiality. One of the requirements of the tower is that it must be free-standing, which means it must resist gravity. Computer- and VR-based formats can simulate gravity using three-dimensional software programs such as Unity™. Also, the 3D-format simulates reality, offering the opportunity for flexibility and therefore variety in tower design. Additionally, the simulation software can rapidly calculate total cost based on the fixed unit cost of user-selected materials. Finally, computer- and VR-based format simulations can be augmented with add-ins.

RESEARCH QUESTION DEVELOPMENT

This research involved development and testing of computer- and VR-based simulations of the Marshmallow TVD Simulation. Simulation development required transformation of the physical simulation. Testing and analysis of the learning effectiveness of the two simulations required determining the moderator effect of perceived usefulness and usability of the advanced formats. Two research questions were posed:

Research question 1. Are there differences in knowledge retention for physical- vs. computer- vs. VR-based formats?

Learning effectiveness refers to the extent to which a goal or task can be achieved. This research investigated whether the different simulation formats affect a users’ knowledge retention. It was investigated by evaluating instructional content after playing the simulations.

Knowledge retention was measured regarding: (a) mutual respect and trust; (b) mutual benefit and reward; (c) collaborative innovation and decision-making; (d) early involvement, (e) early goal definition; (f) intensified planning; (g) open communication; (h) appropriate technology; and effectiveness of the (i) organization and leader. These characteristics represented fundamental TVD principles intended to be conveyed through the Marshmallow TVD Simulation (Munankami, 2012), and were adopted for the consistent assessment of the three different simulation formats.

Research question 2. What is the effect of perceived usefulness and usability on knowledge retention for computer- and VR-based formats?

As computer- and VR-based formats adopt advanced technologies, a users’ attitude toward technology works as an essential factor in learning effectiveness. Serious games and simulations should be usable regardless of a user’s personal characteristics (Jordan, 1998). Two elements, perceived usefulness, and usability, determine the users’ attitude toward the technology (Davis, 1989). This research hypothesized that these qualities moderate knowledge retention in computer- and VR-based simulations, as shown in Figure 1.

Perceived usefulness refers to the degree to which a user believes using a particular technology and system will enhance their performance. Usability refers to the level of comfort users feel and how confident they are with the simulation's capacity for them to reach specified goals (Davis, 1989). These qualities are determinants of a good user experience (Diefenbach et al., 2014; Jordan, 1998) and they help guarantee the success of learning effectiveness in computer- and VR-based formats (Pal & Vanijja, 2020).

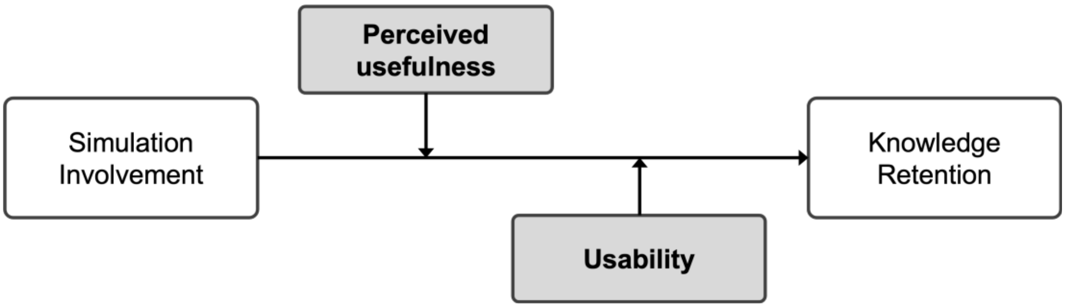


Figure 1: Conceptual Diagram for Research Question 2.

SIMULATION DESCRIPTION

COMPUTER-BASED MARSHMALLOW TVD SIMULATION

This research developed computer- and VR-based formats of Marshmallow TVD Simulation using Unity™. The 3D-software is often used for gaming and can: imitate the properties of materials with some sense of reality; simulate physical characteristics including movement and gravity; provide a user-friendly user interface; and allow multiple networking (Unity User Manual, 2020). The rules and goals of the physical format of the Marshmallow TVD Simulation were transformed into computer- and VR-based formats. Figure 2 shows how key scenes in each format were realized.

The computer-based format requires a three-button mouse (e.g. two buttons and a wheel), as well as a keyboard. Users can select objects in the scene, rotate, place, and delete the object, turn the camera, and zoom in and out with the mouse and keyboard. The computer-based format also provides a graphical user interface that allows users to interact through graphical icons in the scene.

VIRTUAL REALITY MARSHMALLOW TVD SIMULATION

The VR-based Marshmallow TVD Simulation requires users to wear a VR headset and operate controllers. There are two buttons in each controller: the grab button and the trigger button. Grab buttons are located near a user's palm and allow them to grip and release an object. Trigger buttons are operated by index fingers and enable users to activate functions such as a "gravity test" in the VR environment. To a large extent, motions and actions are similar to playing in a physical environment, so users can intuitively understand their manipulations. In the VR-based format, the following were included: a graphical user interface, a panel itemizing materials, costs, and test/return buttons.

SIMULATION TESTING

A post-simulation questionnaire was conducted to investigate the two research questions. Students majoring in construction science, architecture, and civil engineering were recruited; 32 and 26 responses were collected in computer- and VR-based formats, respectively.

Following play, participants were asked to score on a scale of 1 (lowest) to 5 (highest) their perception of the simulation's ability to impart the following key TVD concepts: (a) mutual respect and trust; (b) mutual benefit and reward; (c) collaborative innovation and decision-making; (d) early involvement of key partners; (e) early goal definition; (f) intensified planning; (g) open communication; (h) appropriate technology; and effectiveness of (i) organization and leadership. These data were compiled and compared to identify whether there are statistically significant mean differences between various formats. Previous experimental data from Munankami (2012)'s physical format were used as a control group for the first research question. For the second research question, participants were asked about their perceptions of the simulations. They evaluated the perceived usefulness and usability of the simulations.

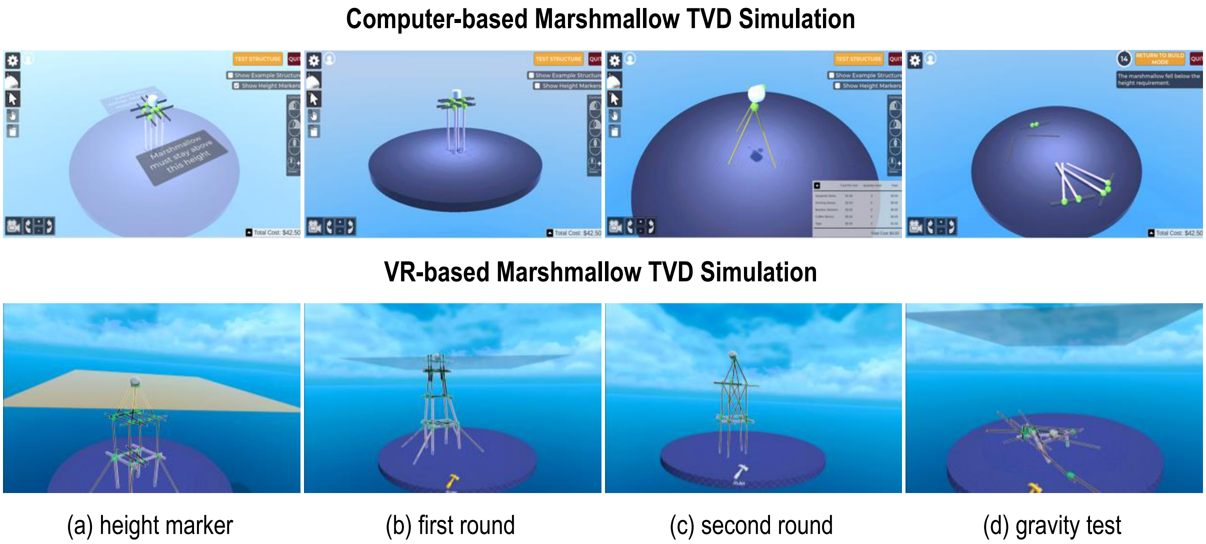


Figure 2: Computer (keyboard)- and VR (headset)-based Marshmallow TVD Simulations

ANALYSIS AND RESULTS

RESEARCH QUESTION 1. ARE THERE DIFFERENCES IN KNOWLEDGE RETENTION FOR PHYSICAL- VS. COMPUTER- VS. VR-BASED FORMATS?

A one-way analysis of variance (ANOVA) was conducted to investigate whether the computer- and VR-based Marshmallow TVD Simulations show a similar or even better understanding than physical simulation.

From the ANOVA, a significant effect of different simulation formats was observed on seven out of nine TVD principles; (a) mutual respect and trust [$F(2, 103) = 6.286$, $p = .003$], (b) mutual benefit and reward [$F(2, 103) = 3.367$, $p = .038$], (c) collaborative innovation and decision-making [$F(2, 103) = 4.967$, $p = .009$], (e) early goal definition [$F(2, 103) = 14.629$, $p < .001$], (f) intensified planning [$F(2, 103) = 8.613$, $p < .001$], (g) open communication [$F(2, 103) = 4.739$, $p < .011$], and (i) organization and leader [$F(2, 103) = 3.763$, $p = 0.026$].

A Tukey HSD test was used for post hoc comparisons of the seven TVD principles to compare each of the different formats to every other format; that is, the test compared understandings of TVD principles from physical- and computer-based, physical- and VR-based, and computer- and VR-based formats. Overall, results indicated that the mean score for the VR format was significantly different from the computer-based format, implying that the VR simulation can more effectively impart the principles of TVD than the physical simulation. The computer- and VR-based formats did not significantly differ in conveying TVD principles except for (e) early goal definition. Early goal definition was most effectively imparted in the VR-based version, followed by computer-based and physical formats (Table 1).

Two TVD principles, including (d) early involvement of key partners and (h) appropriate technology, did not show statistically significant differences. The result means that those two principles can be imparted effectively regardless of the simulation format used. In summary, the VR-based format is superior to other formats in imparting fundamental TVD principles. Some principles can be effectively imparted regardless of the simulation formats, others can be more effectively transferred to a VR-based format. Computer-based and physical-based formats showed very similar levels of effectiveness.

Table 1: Result of Tukey HSD Test

TVD Principle	Mode (I)	Mode (J)	Mean Difference (I - J)	Std. Error	Sig.
(a) Mutual respect and trust	VR	Physical	.579	.164	.002
(b) Mutual benefit and reward	VR	Physical	.442	.173	.032
(c) Collaborative innovation and decision-making	VR	Physical	.492	.156	.006
(e) Early goal definition	VR	Physical	.752	.152	<.001
	Computer	Physical	.552	.142	<.001
(f) Intensified planning	VR	Physical	.686	.166	<.001
(g) Open communication	VR	Physical	.489	.159	.008
(i) Organization and leader	VR	Physical	.556	.207	.022

(Note: Only statistically significant results from the Tukey HSD test are included above.)

RESEARCH QUESTION 2. WHAT IS THE EFFECT OF PERCEIVED USEFULNESS AND USABILITY ON KNOWLEDGE RETENTION FOR COMPUTER- AND VR-BASED FORMATS?

A moderation analysis was used to determine whether the relationship between users' involvement and knowledge retention was influenced by or moderated by usability and usefulness. Four moderation analysis models were created for this research: (1) usability's moderator effect in computer-based format mode; (2) usability's moderator effect in VR-based format; (3) usefulness's moderator effect in computer-based format; and (4) usefulness's moderator effect in VR-based format. Among the four models, the usability's moderator effect in computer-based format showed statistically significant results, as shown in Table 2. The results indicate that the usability of a computer-based format reduces the positive relationship between users' involvement and their understanding of TVD principles (R^2 = .311, $F(3, 28)$ = 4.499, p = .043).

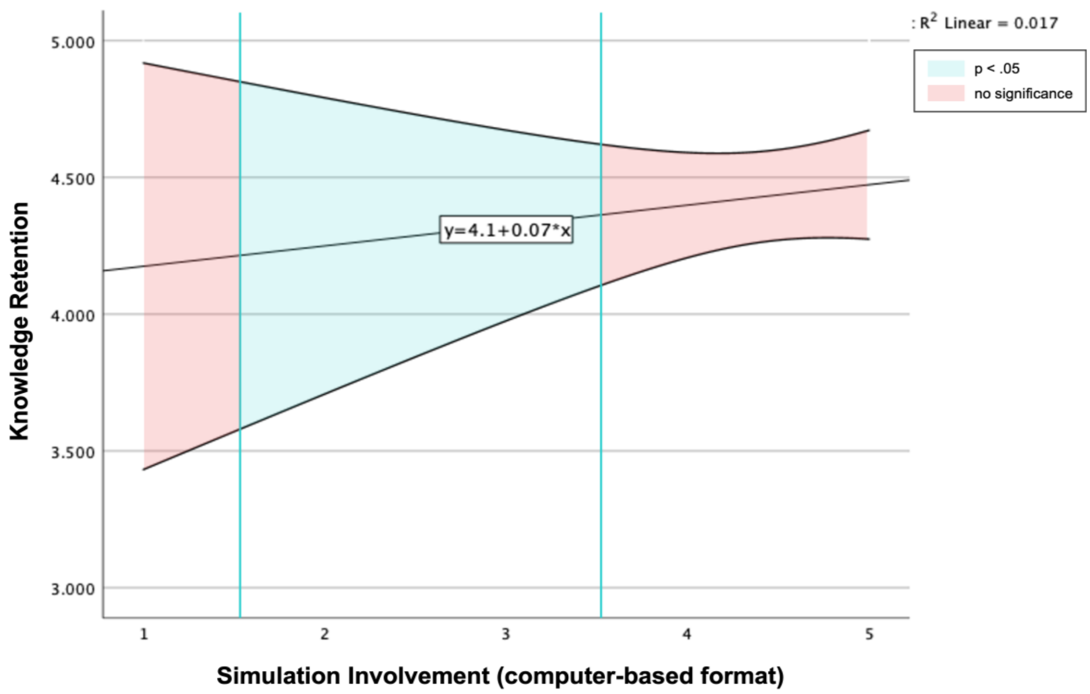
Johnson-Neyman interval further investigated the range of usability where the moderator effect is statistically significant. As a result, the moderator effect of usability on the relationship between the involvement and understanding of TVD principles was significant, from 31.25% to 68.75%; if further increased, there is no moderating effect of usability (Figure 3). The result implies that if the usability is between 31.25% and 68.75%, the effectiveness of the computer-based format can decrease even though there is a positive correlation between the users' involvement and their understanding of TVD principles.

Previous studies have reported that the success of serious games and simulations lies in the active involvement of users playing them, and the more actively and intensively involved the learning process, the better the understanding that emerges (Ropes, 2013; Ypsilanti et al., 2014). However, depending on the usability of the serious games and simulations, specifically in the computer-based format, effectiveness can be changed. Thus, it is crucial to improve the usability of the computer-based simulation to guarantee the maximum level of learning efficacy.

Table 2: Moderation Estimates

	Coeff	SE	t	p	LLCI	ULCI
(1) Usability's moderator effect in the computer-based format						
Involvement	1.629	.741	2.198	.036*	.111	3.147
Usability	1.634	.717	2.280	.031*	.166	3.102
Involvement × Usability	-.334	.158	-2.121	.043*	-.657	-.011
(2) Usability's moderator effect in the VR-based format						
Involvement	1.107	1.122	.987	.334	-1.220	3.434
Usability	1.117	1.100	1.015	.321	-1.165	3.400
Involvement × Usability	.272	.240	1.134	.269	-.770	.226
(3) Usefulness's moderator effect in the computer-based format						
Involvement	.740	.527	1.404	.171	-.340	1.820
Usefulness	.769	.544	1.412	.169	-.347	1.885
Involvement × Usefulness	-.143	.114	-1.252	.221	-.377	.091
(4) Usefulness's moderator effect in the VR-based format						
Involvement	.320	.901	.355	.726	-1.549	2.189
Usefulness	.409	.927	.442	.663	-1.513	2.332
Involvement × Usefulness	-.040	.196	-.204	.840	-.445	.366

*(Note: * signifies statistically significant relationship.)*



Note: X-axis indicates the level of simulation involvement (1: least involved, 5: actively involved). Y-axis indicates users' knowledge retention (1: very low understanding, 5: very high understanding). Usability has a moderator effect in the range highlighted in blue (involvement 1.56 – 3.41).

Figure 3: Johnson-Neyman Plot - Usability's Moderator Effect in Computer-based Format

DISCUSSION AND CONCLUSION

This research investigated the effectiveness of different simulation formats, namely physical-, computer-, and VR-based formats, on a users' knowledge retention. Computer- and VR-based formats of Marshmallow TVD Simulations were developed and used to investigate two research questions.

Empirical results indicated that the VR-based format is superior to other formats in imparting fundamental TVD principles, while some TVD principles, including early involvement of key partners and appropriate technology, can be imparted effectively regardless of the simulation format. Physical- and computer-based formats showed similar effectiveness in imparting TVD principles except for early goal definition. In addition, the usability of a simulation can moderate the learning effectiveness of the computer-based format. From this we learned that developers need to guarantee a high level of usability, specifically when engaging users in a computer-based format.

This research provides insights that can be instructive for future serious game and simulation developers. Simulation developers, especially those who intend to develop a computer-based format, should take care to improve usability to maximize learning effectiveness. This research identified the relatively unexplored area of moderator effectiveness for perceived usefulness and usability. By extending the results to other serious games and simulations, different modes can be adopted to be effective for a wider range of participants.

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INCORPORATING PSYCHOLOGY OF LEARNING THROUGH THE MALABARES METHOD FOR EFFECTIVE IMPLEMENTATION OF THE LAST PLANNER SYSTEM

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ABSTRACT

This study investigates the impact of teaching through a method developed by a chilean company, Malabares Consultores, based on psychology of learning theories and in the adherence to the Last Planner System methodology. It takes a qualitative and descriptive approach to the teaching of LPS by implementing this so-called the Malabares method, that is a compound of six key factors, as is described in the present document. The study shows the evolution of this method in three stages of development, where the learning obtained in each stage is analysed as well as the adjustments made to improve it. The results show that through the security, confidence and willingness to learn of the participants, added to the gamification of the contents, a link is generated between teacher and student that allows the LPS methodology to be transmitted very effectively both to the person and to the company a la whole. On the other hand, transversal participation from the entire team, including administrators and on-site managers, added to an implementation program that trains work teams at their own workplaces, supporting teams in generating the planning habit under de LPS in the long term, are proven to be crucial to success. The study provides evidence for the effectiveness of the Malabares method in the construction industry and concludes that it offers a valuable approach to implementing the LPS, emphasizing the importance of continuous improvement within the method development example itself.

KEYWORDS

Serious games, simulations, action learning/research, trust, collaboration, Last Planner ®System.

INTRODUCTION

The need to change to survive is observed and understood in both plant, animal, and human nature, as well as in competitive organizational environments. Plants and animals must adapt to their habitat conditions, available resources, and predator threats. Humans must learn to live in an increasingly inclusive and technologically advanced multicultural society. Companies

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must figure out how to compete and meet the new needs of people, the changing society values and the other companies threats (Hamel, 1996; Yoon et al., 2019). Facing these diverse realities, change results from the transition of an individual or group of individuals from their current condition to a new one that allows them to face aspects of their environment that they could not in their current state (Hamel, 2000).

The change or changes, in the case of human beings, and therefore in the organizations that they make up, can be conducted and achieved through the teaching-learning process, which in turn can occur in different ways according to how the person processes the information he receives and how he transforms it into knowledge, either reflecting or experiencing it in a concrete way. Finally, this process can be promoted and even ensured with the use and planning of methodologies, that is, with strategies, procedures and actions ordered in such a way that they allow the achievement of the objective of facilitating student learning.

Regarding organizations, the change requires learnings to adapt its methods and policies at the level that is necessary, to effectively be profitable in the face of the market and self-conditions (the only path that does not mean ceasing its activities of course). This need for change may not be evident or may not necessarily have to be resolved in the short term, but the organization should be aware of the possible need in the long term (Drucker, 2012). You can be in a healthy health condition today, but given the dizzying social, technological, and competitive changes, the current condition may not guarantee survival in future social, technological, or competitive contexts. Thus, the need for change, or at least the ability to change, presents itself as a relevant and interesting aspect for any organization that aspires to continue operating tomorrow (Abraham, 2012).

But, how to prepare for this change, and how to effectively carry it out? Nature takes its time, evolutionary changes take hundreds, thousands, and even millions of years. It is humble for humans to understand that their own changes cannot happen overnight (Commoner, 2020). There are things that should be approached gradually and sustained over time to see positive and permanent results (Abraham, 2012). Strict diets that seek results in a few days often have negative effects and eventually lead the person to a worse situation than the original (Sidor & Rzymski, 2020). Sudden implementations of new work methods in an organization make it difficult for workers to understand, adhere to, and use these, leading to the failure of their implementation or to the turnover of their workers, affecting the human group that makes up the organization (Bortolotti et al., 2015). Changes must be approached gradually, to give the organization time to be able to change, being one of the first conditions that the members of the organization, at its different levels and hierarchies, are open to change. It is about generating a culture that allows it to effectively implement the specific changes required in various situations (Drucker, 2012). Given this context, the Lean philosophy and the concept of continuous improvement are conceived as a way of being, thinking, and doing that, when implemented and rooted in an organizational culture, contributes to an organization as a whole being more efficient, effective, and flexible (Bhasin & Burcher, 2006; Pellicer et al., 2015).

Lean philosophy and continuous improvement are considered key elements in generating a culture of change within an organization (Dave et al., 2013; Howell et al., 2004). The question now arises, how to introduce this philosophy in an organization, both in its work methods and operation and in its group of collaborators? It must be gradually introduced to ensure its correct understanding, adherence and permanence at both individual and organizational levels (Alsehaimi et al., 2014). Intensive inductions for the entire work team do not guarantee effectiveness, as they can confuse and the natural tendency will be to return to the familiar, in this case, to how things were done before the induction (Salazar et al., 2019). The implementation process of a new work methodology in a group must consider not only the introduction of this new knowledge but also its sustained implementation over time, ensuring the necessary accompaniment and adjustments that may be required based on the results obtained (Dave et al., 2015). Finally, it is about developing a continuous improvement process in the use and growth of the new knowledge by the organization (Hu et al., 2016).

Learning styles are the result of the combination of two ways in which individuals process information from lived experience. The first way to process information is by living the experience in a direct and concrete way, involving emotions through challenging and short activities with quick results. The second way to process information is through abstract experience, when the individual reads or someone tells him something. In addition, two ways of transforming information into knowledge are identified in people, the first occurs in the reflective student, who analyzes experiences from many different points of view, and the second occurs by concretely experiencing the information received, where the individual puts into practice the new knowledge acquired.

The mentioned is complemented by other theories on the nature of human learning at the individual level that emphasize the importance of concepts such as meaningful learning, which means that new knowledge must be linked to the individual's interests, and situated learning, which is when the new knowledge must be put into practice in the individual's real-life activities so that they can demonstrate its impact and usefulness. In both cases, learning is achieved by giving meaning to what is being learned, whether at a personal or work level.

In addition, the "teacher's work" becomes key to using the learning potential in the human being, since it is the teacher who best perceives the different styles and ways of learning of their students, generating techniques and environments suitable for learning. the learning and change that is sought based on the people with whom one is working. The teacher will act as a mediator between the experiences, the environment and the new learning, generating a security, bond and trust in the environment to encourage all these variables to combine harmoniously in people (Feuerstein, 1980).

Today, the so-called Malabares method, developed by the company Malabares Consultores, is formally defined as the integration of six factors that, applied correctly, make it possible to modify people's work habits. It has been proven in the implementation of the Last Planner System (LPS) in companies of the construction industry in Chile, and also in the implementation of other Lean methodologies. These factors are: (1) A space of security and confidence; (2) Learning “here and now”; (3) Transversal participation of the organization; (4) An implementation program through trainings, training sessions and accompaniments; (5) Interactive dynamics for meaningful learning; (6) Long-term work program that ensures adherence to the methodology. With the above, the method permeates the work teams, generating a positive experience and a long-term adherence and permanence of the methodology in everyone, both in individuals and the company, which ultimately contributes to the necessary ability to survive in the changing and competitive environment of today's business organizations, particularly in the construction industry. The purpose of this work is to present and describe this method from its conception to the proven success of its use today, to contribute, as a case study, to the teaching-learning processes of this and other methodologies.

RESEARCH METHOD

The aim of the study is to demonstrate the impact of the Malabares method on adherence to the Last Planner System (LPS) methodology and to verify changes in adherence indicators resulting from the method's application over time. The study employs a qualitative approach to study phenomena and subjects within their contexts and find meaning in them based on people's own interpretations. The study is descriptive, analyzing the characteristics of the training process and the profiles of the participants using the Malabares teaching method as the phenomenon under investigation. The authors seek to verify effective adherence to the LPS methodology and describe the impact of the Malabares teaching method on this adherence .

The population studied consists of collaborators from companies trained by Malabares and collaborators from Malabares itself who have witnessed the changes and results obtained from the training developed over time. A non-probabilistic sample was used, with convenience sampling for trained companies that agreed to participate and purposive sampling for members of Malabares who participated in the trainings and witnessed adherence in the trained teams. The trained companies are among the most relevant in the construction industry in Chile, including one operating in the stock exchange, and their collaborators mostly hold managerial positions or are area managers with experience in construction, planning and team coordination, and have previously implemented methodologies, including LPS. The Malabares collaborators are a team of people from the areas of engineering, psychology, communication and academia, with 10-20 years of individual professional experience in their respective fields and at least 3 years implementing the methodology. The co-founders, Andrés and Guillermo, have 15 years of experience in LPS and active teaching, respectively.

The study utilized semi-structured in-depth interviews as well as existing documentary data on the results of the training and implementation of LPS by Malabares. The in-depth interviews were designed based on Mertens' typology, which aimed to obtain background, opinions, and expressions of feelings from the subjects of the study. The documentary information had two main sources: the results of adherence and permanence of LPS measured by the companies themselves, and Malabares' own information gathering through evaluations of adherence to the methodology during periodic visits. This evaluation involved scoring key steps of the meetings, commitments, and fulfillment of tasks by the work teams, with possible outcomes of 0%, 50%, and 100% depending on the execution and achievement of the objectives.

Through this research methodology, the effectiveness of the Malabares method in different implementations was evaluated by comparing expert opinions and empirical data. The study established three stages in the life of the Malabares method: the initial stage, the transition stage, and the current stage, with each exhibiting different characteristics and results. To present the findings, graphs were included for each stage, showing the results of the evaluation of adherence to the methodology of different works during the accompaniment stage (three cases per each accompaniment stage).

THE “MALABARES” METHOD

For the past 9 years, Malabares Consultores has been working to implement the last planner system (LPS) in the construction, real estate, and other industries in Chile. Their approach aims to promote learning, adherence, and long-term retention of this new knowledge. The results of Malabares' work over the years have demonstrated concrete and lasting benefits such as better effective communication within the teams, greater efficiency in meeting planning, and adherence and persistence of new knowledge at both the individual and company levels.

Malabares' implementation of the LPS initially focuses on three planning instances: the Master Plan, Intermediate Plan, and Weekly Plan. The Master Plan provides a strategic vision of the project, identifying deadlines, activity sequences, and milestones traditionally presented in a Gantt chart format. The Intermediate Plan analyzes the activities of the project from a horizon of 4-6 weeks, identifying the detailed sequence of each activity, the necessary resources and the restrictions to guarantee that all the conditions are available so that the deadlines of the project can be met. Finally, the Weekly Plan is a short-term weekly schedule expressed as an expected progress schedule, which is then analyzed by the responsible parties to create a credible engagement schedule. The philosophy of "continuous improvement" is introduced with the commitment program that is reviewed and validated during the Intermediate and Weekly Planning meetings, where the fundamental root causes of unfulfilled commitments are identified and corrective actions are established to prevent recurrence. The goal of Malabares' implementation is to enable teams to apply the concepts and tools of the LPS and establish the weekly use of Intermediate and Weekly Planning meetings.

ORIGIN OF THE "MALABARES" METHOD

Malabares Consultores S.A. was founded with the goal of teaching the LPS methodology to construction companies in Chile through a pedagogical approach that uses games. The founders had previously observed unsuccessful attempts to teach and implement the LPS methodology through traditional methods, where people struggled to understand and apply the concepts. One of the co-founders, an industrial civil engineer, had experienced this firsthand while working on teams that attempted to use the LPS methodology. Despite being convinced of its benefits, he found that there was a lack of an environment that promoted easier and more effective teaching at a conceptual level while visualizing and concretizing the practical application of what was taught. On the other hand, the other co-founder, a psychologist, believed that people could learn and apply any work methodology if they were in a favorable environment with reduced stress levels and if the content taught made sense to them. These two perspectives led to the idea of using play experiences to teach the LPS methodology, encouraging the participation of the entire team. As the psychologist explained, "the engineer believed in the method, and I believed in people". The goal of using this approach is to ensure that the teams can grasp and internalize the concepts of the methodology and apply them effectively to their work, resulting in improved teamwork and adherence to the LPS methodology.

THE SIX KEY FACTORS OF THE "MALABARES" METHOD

The method can currently be described in six key factors, those that arise from the initial purpose of its founders and are consolidated with the passage of time and the continuous improvement developed on the implementation process itself. They are described below:

(1) A space of security and confidence: Malabares Consultores emphasizes the importance of establishing rules at the start of workshops, such as arriving on time and actively listening to others. These rules provide a sense of security and care for all participants, and also values the experience and knowledge of the participants, encouraging mistakes as a natural part of the learning process. Trust is established through empathetic listening and validation of comments. As the group bonds, humor and laughter are encouraged to lower barriers and promote learning. To prepare the workspace, tables are set up with paper, markers, sticky notes… and candies.

(2) Learning "here and now": The importance of attending with a willingness to learn is explained to the participants, asking them to concentrate on what is being discussed and the experiences that are being shared. This also means surrendering to the dynamics, wanting to play, move, share and open up to others. To encourage participation, induce the game and reward those who answer correctly, chocolates are distributed among the participants.

(3) Transversal participation of the organization: This is key in trainings, where entire real teams, including managers, administrators, field professionals, supervisors, warehouse, technical office, and subcontractors, are invited to participate in the same learning space. This generates positive bonds during training and then taking them to the field. When everyone participates in the presentation of new knowledge, language and meaning align, and technical concepts, for example the "restrictions", are understood and used throughout the organization.

(4) An implementation program through trainings, training sessions and accompaniments: This 3-step program aims to provide the necessary theoretical and practical knowledge to apply the LPS methodology on site. Participants are trained in the necessary tools to carry out intermediate and weekly planning stages, such as the "analysis sheet" or the "weekly program", and then are taught a step-by-step methodology, considering the different roles and responsibilities of each member of the team. Accompaniments consist of scheduled visits to the planning meetings, evaluating adherence to the methodology, with six to ten visits per team.

The program spans over several months, with training in the first months and accompaniments in the following months.

(5) Interactive dynamics for meaningful learning: To enhance the learning experience, gamification is used within the logical thinking process designed for the participants to explore and discover the meaning of the adopted work method. Two facilitators are always present during the workshops and training sessions: Facilitator No. 1 is the theoretical expert who ensures complete delivery of methodology content, while Facilitator No. 2 ensures active participation and comprehension among all attendees. The use of games and activities helps participants to engage with the material in a meaningful way, leading to greater understanding and retention of the knowledge presented.

(6) Long-term work program that ensures adherence to the methodology: The sixth factor stems from the actual experience of Malabares' application and modifications to the method. This factor is related to the objective and the needs of the companies to ensure that what has been learned is maintained over time, which implies changes in the habits of the teams, for which time is required. The program considers the learning time of each team, which is why the implementations, in their current version, have a duration of 6 to 12 months, where the facilitators, according to their experience, identify the different support needs of each team.

The evolution of the Malabares method in its constant development and how it has impacted the evaluations of adherence to the methodology that are carried out in the program's accompaniment stage will be presented below. Although the changes have been constant, two key modifications over time are identified, which mark 3 stages with characteristics and their adherence results over time. The application of these 6 factors throughout the 3 stages called Initial, Transition and Current Implementation will be discussed.

INITIAL IMPLEMENTATION

The LPS programs carried out by Malabares Consultores from 2016 to 2019 are considered as an initial stage. In this stage, what in now called the Malabares method was only the idea that focusing a training on the learning processes of people with a theoretical content that made sense to them, would ensure changes in habits and use of what was learned. The participants' reception of this new way of teaching was one of total uncertainty.

Both the 1st factor, the idea of generating a safe and trusting space for learning, and the 2nd factor, inviting them to become aware of learning "here and now", were implemented from the beginning and as described in the definition of the method. The 3rd factor, regarding the transversal participation of the team, is a requirement that arises from Malabares, who proposes the participation of everyone (subcontractors, specialists, support areas, etc.), however, it is up to the organization to decide if it finally includes all the related parties or not. On the other hand, it is noted that a real impact is generated in participants commitment when heads and managers attend the workshops. The 4th factor, the implementation program itself, considering the stages training, training sessions and accompaniments, in the first implementations of the LPS for construction companies' teams, were structured with 18 hours of training, divided into 4 modules and then 4 “training sessions”. Finally, there are 2 surprise visits, initially called “monitoring”, to actual team meetings on site for the Intermediate Planning and Weekly Planning meetings. The goal of these visits was to ensure that the meetings are being held regularly on the days and at the times established, and that the tools learned in the training are being implemented. The program as a whole was 60% training, 27% training sessions and 13% monitoring if we consider the time dedicated for each stage, and in general lasted 2-3 months. Regarding to 5th factor, in the initial stage the interactive dynamics for meaningful learning were focused on situations outside the construction. In a safe and trusting space, games and laughter come easily. In the trainings, participants are given costumes and props that are specific to working with Malabares that they would not normally use, especially in a work environment, such as the use of a clown nose every time a participant had to present a concept, which makes the training more fun and less intimidating. The 6th factor, the long-term work program, had not yet been developed at this stage.

The greatest discovery in this initial stage was the link between facilitators and participants that is generated in the trainings. The importance of opening the bond or link in all the initial contact instances in order to teach the theoretical content that is required later on. With the certainty of having found the way to generate the "knowledge transfer bridge" between the participants and the facilitators, there was room to make other modifications.

The results of the evaluations also showed that, although good immediate adherence was achieved by the team, with team members remembering the main concepts of the LPS and the use of the tools (evidenced by an individual test), there were drops in evaluation due to two main reasons: the teams do not have a clear idea of how to apply everything learned to real work situations; and it is difficult to remember the structure of the meetings and replicate them weekly. The surprise visits at the monitoring stage induces the teams to carry out the meetings, but does not ensure the quality, leading in some cases to the practice of these only to comply with the Malabares visit and not to observe real progress with the execution of these (like a student who prepares to get a good grade, but not to really learn the content of the evaluation).

While the playful mode meets the objectives of favoring the learning environment, favoring communication and reducing barriers to changes in work practices, it has a deficiency in achieving that the methodology begins to be applied in a real work situation, so it is concluded that the training should, without completely losing the playful focus, be more focused on the real applications of the methodology and not on fictitious examples unrelated to work. Also, it is concluded that tools must be included to help maintain the adherence to the methodology achieved with the training stage throughout the entire project and not lost and returned to the previous work practices, which are precisely the ones being sought to change and for which the clients decide to develop the implementation of the LPS. The surprise monitoring system, as mentioned, ensures the execution of the meetings but not their quality. Thus, the logical conclusion is that the team visits should aim not only to evaluate the permanence, but also to improve the quality of the content of the meetings and their efficiency, contributing to the effective change in the team's work culture by visualizing the discrepancies that are obtained, thus giving meaning to the new knowledge in their daily work.

Figure 1 shows the results of the evaluation of LPS adherence in three construction projects (at five consecutive evaluation moments) where the initial stage method was applied. The x-axis shows the number of the evaluation for each work, the space between evaluations is from 1 to 3 weeks. The evaluated works are high-rise housing and may correspond to teams in different companies (I1, I2, I3, respectively).

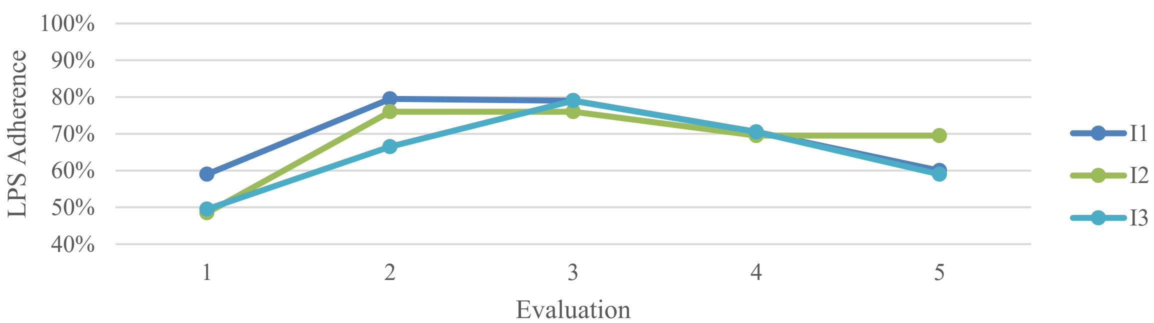

Figure 1: LPS adherence of three construction projects. Initial Implementation

TRANSITION IMPLEMENTATION

The transition stage covers implementations mainly in years 2019-2020. During this stage, the importance of generating a space of security and confidence (1st factor) and of learning "here and now" (2nd factor) was maintained. The participation of actors from different disciplines and positions within the organization (3rd factor) was reinforced and called to be fulfilled. The observations made on the initial stage and the results of the teams create the need to induce changes in the Interactive dynamics for meaningful learning (5th factor) and structure of the implementations (4th factor), aiming to reduce the negative impacts mentioned.

The structure of the Malabares' LPS implementation is now 12 hours of training divided into 4 modules of 3 hours each, 5 training sessions focused on preparing and executing Intermediate Planning and Weekly Planning meetings and 4 accompaniment sessions to strengthen the persistence of adherence to the methodology. The program was divided into 40% training, 47% training sessions, and 13% accompaniment based on the time dedicated to each stage. Increasing the hours of training sessions will result in more personalized teaching, better tool utilization, and earlier realization of the benefits of the methodology. Since it is crucial to prepare for meetings, such preparations should be included in the training sessions as well. The aim is to ensure that team members understand their roles and responsibilities, development and validating the planning information in advance of the meeting, rather than developing it during the meeting itself. The new iteration adds a stage of "accompaniment," consisting of 4 monthly interventions where the Malabares team supports the construction team in the preparation and meeting instances, ensuring better results, unlike the previous surprise visit, which only measured results. Additionally, the items evaluated in this accompaniment are modified to consider not only the step-by-step structure of the meeting but also the main preparation instances that must be respected to ensure the information is ready for presentation. All the applied changes affect the duration of the implementation in approximately one month.

According to the 5th factor, trainings themselves maintained a playful and participatory approach, but changed the games and dynamics that lead the participants to completely fictitious situations to simulations of equally fictional situations but within a construction context that LPS will later be applied in. Thus, the games and activities always talk about construction meetings, field activities such as excavation or concrete structures, and weekly building works programs. Before trainings, participants are asked to go to the field and look for changes in their work such as unused materials or idle times and then expose and develop ideas in the training that are completely adjusted to the project reality.

During the implementation of the LPS methodology, team adherence decreases over time, although there is stabilization and slight improvement during the accompaniment stage. Practical applications of the methodology are learned in trainings and replicated in project development with the support of Malabares, but when the accompaniment stage begins, some fundamental concepts are not clear to all team members, leading to tool abandonment. However, the extension of Malabares' team participation in the work helps maintain the team's application of the methodology, reversing the trend of decreasing adherence and leading to an improvement trend. Individuals from the work teams make personalized contributions, but these are not always shared with the rest of the team, especially in field teams.

After this iteration, it is concluded that the application of playful dynamics with examples applied to real work conditions helps teams understand how the tools of the methodology should be applied to the cases they will see in their work, but it is not a good option for participants to internalize the basic concepts of the LPS individually first. To improve the results of the implementation, it is first necessary to ensure that the team members understand the fundamental concepts of the LPS well, and then to apply these to real work cases. It is concluded and reinforced the idea of maintaining the accompaniment stage for the teams, even dedicating a greater number of hours to this stage and increasing the number of months in which the

Malabares team will continue to work with the teams until stabilizing the adherence indicators. Thus, the need for the 6th factor, long-term work program, is conceived.

Figure 2 shows the results of the evaluation of LPS adherence in three construction projects (at nine consecutive evaluation moments) where the transition implementation method was applied. The x-axis shows the number of the evaluation for each work, the space between evaluations is from 1 to 3 weeks. The evaluated works are high-rise dwellings and may correspond to teams in different companies (T1, T2, and T3, respectively).

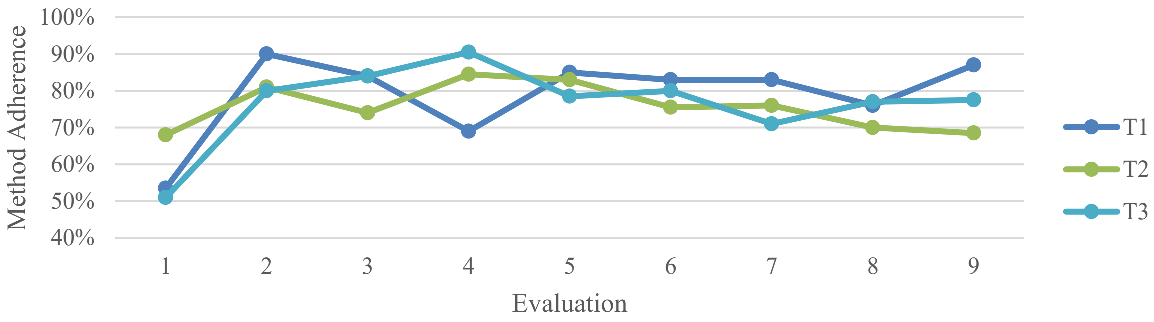

Figure 2: LPS adherence of three construction projects. Transition Implementation

CURRENT IMPLEMENTATION

The current stage started in 2021 and is implemented until these days. The current training of Malabares is characterized by returning to the more playful roots of the method, reserving the examples applicable in real-life work situations for the training stage, and then developing sustained support for several months. In this stage, the focus on generating the facilitator-student bond through the space of security and trust (1st factor) and learning "here and now" (2nd factor) is paramount. Regardless of the culture of the company or the characteristics of the people who attend the implementations, positive emotions are contagious, and everyone is open to play, to enriching discussions and to sharing experiences. Interactions between people are essential, giving the necessary time to each type of learning. Regarding the transversal participation of the agents involved (3rd factor), it remained the same as in the previous stage. Managers, supervisors, and supervisors are indispensable in the presentation of the complete program, where they support and validate the program itself to be implemented.

At this stage the complete program lasts 12 months, convinced of the importance of supporting the teams in adopting the habit in the long term (6^{th} factor). The new structure of implementation program (4th factor) currently contains the following: 6-hour instruction divided into two 3-hour modules, where the aim is to teach the main concepts of the method and its application to fictional cases. 2 training sessions for the Intermediate Plan and 2 for the Weekly Plan. Accompaniment until completing 12 months of implementation in the team, which are maintained as instances where the construction team is supported to prepare the meeting and then evaluate it, pointing out opportunities for continuous improvement in front of each evaluation. The participation of each stage in this program is: training 12%, training sessions 31% and accompaniment 58%. The current composition of the program takes better care of the characteristics of the learning process of the participants, giving space for those who have different ways of learning to become users of the methodology.

The 5th factor in the current implementation program incorporates all the experience gained during these almost 10 years. All the dynamics of the training are aimed at getting the participants to reflect on the reasons behind the theoretical concepts, for example: Why to plan? Why to live a Lean culture? Why be aware of continuous improvement? Each answer to these questions is shown applied in their daily work and personal life through games, examples and analogies. So later, they feel the need and possibility of generating the change because they know and validate the benefits it brings. Also in the current stage, new work instances are added with execution teams on the ground in continuous improvement meetings of 30 minutes, where the goal is to assess improvement opportunities observed by the field teams, to seek solutions applicable by the team, and to propose action plans to implement the improvement.

In this stage, work teams have similar level of adherence to previous cases and even better, but, unlike previous cases, with the transition to the training and accompaniment stages, a tendency to improvement or stabilization is maintained in high levels of adherence. The continuous improvement work with the field teams allows for an assessment of multiple improvement opportunities, in many cases unknown to the administrative professionals in the team, which are reported to the rest of the team along with solution proposals, which denotes proactive and positive work from the field teams in favor of good execution of the work. Although at the time of this study, the implementations of this method have not yet concluded, it is observed that in the evaluations of the support stage, a trend towards improvement is maintained without abrupt drops compared to previous implementation stages. Applying what was learned to real-life cases, which are closer to the work conditions of the teams, is also key to good implementation, if it is started once the fundamental concepts underlying these practices have already been learned and internalized by the team. Finally, in cases where significant deviations from the method are observed in the team, it is concluded that an immediate alignment should be made with the team to adjust group adherence.

Figure 3 shows the results of the evaluation of LPS adherence in three construction projects (at three consecutive evaluation moments) where the current implementation method was applied. On the x-axis is the number of the evaluation for each work, the space between evaluations is from 1 to 3 weeks. The evaluated works are high-rise housing and may correspond to teams in different companies (C1, C2, and C3, respectively).

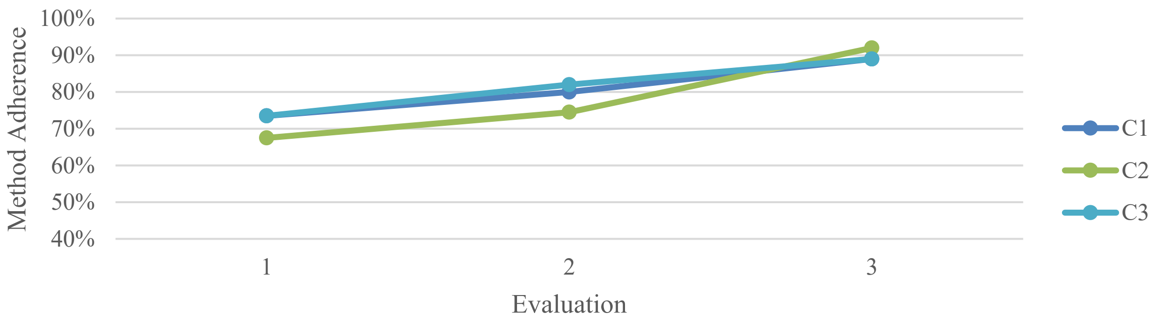

Figure 3: LPS adherence of three construction projects. Current Implementation

CONCLUSIONS

The implementation of the Last Planner System methodology under the method created by Malabares Consultores has proven to be efficient and lasting over time, since it allows for substantial and profound changes, generating a new way of understanding and seeing different situations, breaking paradigms and building new ones, thanks to the fact that it takes into account the environment in which people find themselves, whether at work or personally, the experiences of each participant, their biology in terms of the intellectual capacity of each one, among other factors.

Interventions in a learning environment are never the same, because the contexts and the people who learn are different. The Malabares teacher takes into account the different types of learning that each student has and through various dynamics achieves the participation of all, with which a greater diversity, points of view and experiences are obtained around the new knowledge that is being taught and to its application in real daily work. Different activities and games are developed where the abilities of each one help the learning of the other, since they are put in situations and roles to which they are not used, where they have to listen, read, act, teach, reflect together and achieve the adequate synergy for learning and the sense of what is transmitted. This not only serves to better "understand" the subject, but also to generate an environment of trust and bonds between all the participants, which is finally transferred to the actual work on site, where people manage to connect what they have learned during the training. and apply it in their daily activities, and at the same time consolidate a work team that learns and advances as a whole.

It should be noted that the main limitation of the study is that although quantitative data was used, most of it was qualitative, so a much more detailed quantitative study of the adherence results could be developed in the future, and thus validate the Malabares method more accurately. All in all, it is possible to affirm that the six key factors through which the Malabares method is expressed can be useful for any type or area of knowledge, not exclusively LPS, that it is necessary for a team or commercial organization to acquire. Finally, the case presented in this study can be expressed as an example of continuous improvement in itself, this being a key concept within the Lean philosophy, and a necessity for the survival of human beings and companies.

In summary, the implementation of LPS with the Malabares method has shown that an effective way to teach this methodology and achieve good adherence to the team is by creating a close bond between people, as well as a pleasant and relaxed environment, regardless of hierarchies within the team and organization. Constant support over time, not only in training, but also in monitoring workers in the field, is essential for long-term adherence to the Last Planner System methodology. Learning effectively lasts over time thanks to the creation of new cognitive structures, mental maps and significant memories. Malabares believes in people, in their abilities and that it is never too late to face new challenges, and he puts this into practice with great passion in all his interventions.

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TEACHING AND TRAINING EFFORTS OF ACADEMIA AND INDUSTRY TOWARDS LEAN CONSTRUCTION IN INDIA

Prashanth Kumar Sreram[1,2] and Albert Thomas[3]

ABSTRACT

Lean construction is gaining traction in India. While there are a few companies which have become first movers and gained advantages of lean implementation in construction projects, there still are many companies which still need to adopt lean construction. At this juncture, the role of academia and industry is vital for accelerating lean implementation. However, the studies indicating lean teaching and training efforts are limited in the Indian context. Therefore, research is conducted to explore how Indian construction companies are adopting lean and how academia is contributing to lean construction, which is the aim of the study. Multiple research methods are used to obtain information on lean implementation. The results indicate that organisations have started lean implementation mainly for cost and time benefits, but there is a difference in training their employees and trade partners. Academia is teaching lean construction majorly as an elective than as a compulsory course. Further, measures to accelerate lean implementation in India are proposed. Overall, this paper presents the efforts of industry and academia towards lean implementation in India and is a source of information for construction companies in emerging and developing economies wishing to initiate the lean journey.

KEYWORDS

Lean construction, collaboration, education, process, change.

INTRODUCTION

One of the largest industries in the world on a global scale is construction. Around 7% of the world's working population is employed there. Every year, more than $10 trillion is spent on construction products and services, which is equal to 13% of the GDP. According to Invest India (NIPFA (n.d)), an official Government of India database, India's construction industry is anticipated to contribute about 9% of the nation's GDP and employ 51 million people. By 2025, it is anticipated to reach USD 1.4 trillion as one of the major economic sectors in the world is constructed. The industry supports 7% of the world's working population and has an impact that extends far beyond its borders by creating the buildings where we live, work, generate our energy, produce our materials and goods, and travel. However, compared to other sectors, the

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construction industry's productivity has been appallingly low for decades (Ramaswamy & Kalidindi, 2009).

Adopting Lean tools and principles can help the construction industry improve its operational efficiency, promote collaboration with business partners, and thus enhance its ability to deliver projects as per the commitments made to customers more consistently. Moreover, it would help the organisations improve their overall business performance. Similarly, introducing any new philosophy requires sufficient training efforts, either through in-house training or academic institutions (Moradi, Sormunen 2013, Raghavan et al., 2014, & Bayhan et al., 2019). However, the research in this direction is limited in the Indian context. Therefore, this research work aims to understand the current level of efforts in teaching and training in India. Further, the following research questions were focused upon: How typical or different is the lean implementation in Indian construction companies? and How are the companies and academia engaging in lean training and teaching?

This study summarises the journey of lean implementation in a few client, consultant and contractor firms in India and provides an overview of the current situation from the perspective of lean implementation engineers and academicians and is helpful for researchers and practitioners in developing countries.

LITERATURE REVIEW

In order to understand the current status of lean implementation, the International Group for Lean Construction (IGLC) and Lean Construction Journal (LCJ) are the primary sources of literature. A keyword such as "India", "Lean construction", and "Lean implementation" were used to search for the literature in the IGLC conference papers. Various researchers across the globe have studied lean implementation.

Smith & Ngo, 2017 studied lean implementation by finishing contractors in the United States and observed that Last Planner System (LPS) was the most common tool used. The driving force for lean implementation is cutting costs and reducing schedules. Mossmon (2009) has mentioned that the need for lean education is one of the reasons for no more implementation in the UK. In the case of Brazil, Valente et al., 2020 have observed that in a case study company, various initiatives like participating in lean conferences, using LPS, encouraging continuing education, and lean training for partners as the main success factors for lean sustaining. Forbes et al., (2021) have presented case study examples of lean education initiatives by US-based Owners, Architect, Engineering, and Construction (OAEC) stakeholders based on semi-structured interviews.

In the Indian context towards lean implementation, Karanjawala & Baretto, 2018 have provided case studies of implementing lean at multiple project sites in India. Raghavan et al., (2014) have identified that in Indian construction, lean implementation is subject to factors like site and organisational culture, planning and engineering expertise, and site and top management support, based on the experience of working with a contractor and client firm in India, Kalyan et al., (2018) have proposed that lean tools at the site level, as a bottom-up approach and then that can be complemented with a top-down approach that builds awareness, empathy, and knowledge at the leadership level. Further, Anandh et al., (2018) have observed that lean implementation through academia could be much higher in India and have suggested measures to add Lean construction in India.

The above literature indicates that there are studies on lean implementation in various countries, including India. However, in the Indian context, the existing literature is reported primarily by the institute/organisation implementing lean as their experiences, which is a perspective from the top level. Further, studies indicating teaching and training efforts similar to Forbes et al., (2021) are unavailable, and there is a need to take a bottom-up approach of enquiring from the project level (Arbulu & Zabelle, 2006). Therefore, there is a need to understand the views of the people who are implementing lean at sites and also from the faculty who are teaching lean. Accordingly, the study aims to explore how Indian construction companies are adopting lean and how academia is contributing to lean construction. Further, the objective is to identify potential commonalities and differences in lean education (training and teaching) and measures to accelerate lean implementation in India. The research necessitates using multiple research methods to achieve the study's aim and objectives.

RESEARCH METHODOLOGY

Multiple research methods, such as desk research, survey form, and case studies, were used to achieve the purpose of the study, with qualitative case study methodology, as a combination of different data collection methods (Pinfield, 1986; Anderson, 1983). Using multiple methods has many advantages, such as increasing the creative potential of the research, and it also allows for covering more details and findings (Kathleen, 1989).

Purposive sampling was used to identify the respondents who are currently implementing lean. Purposive sampling is a non-random sampling technique which is helpful for the researcher in an exploratory study where the researcher finds out who can and will provide information through practice, knowledge, and experience (Etikan et al., 2016). One of the authors participated in Indian Lean Construction Conference (ILCC) held at Hyderabad, Telangana, India, during 15-17 December 2022 to identify the respondents from the companies and academic institutes participating in the conference and approached forty attendees for participating in the survey.

Fifteen participants have agreed to participate in the survey. However, instead of the interview, there was a need for more time as they were busy at the conference and agreed to share their inputs through the web-based survey form. Further, the company/institute where the participant's work is considered a case study example. The selected companies and academic institutions are known for their leadership in lean construction and are playing a pivotal role in the Indian Lean Construction Excellence (ILCE) community in India.

The research methodology involved a structured questionnaire survey (web-based) with open-ended questions for obtaining input from the respondents from the case study companies and educational institutions. Further, the company information is obtained through desk research. The desk research method is used for referring to ILCC conference proceedings, souvenirs, magazines covering lean construction aspects in India, being the members of ILCE, in order to be through with the lean journey of the case companies. Further, a qualitative content analysis was performed on the raw data provided by the respondents. The goal of qualitative content analysis is to summarise the informational elements of the data (Altheide, 1987 & Sandelowski, 2000). As per the request of the repondents, the company names and respondent names are anonymised.

DATA COLLECTION AND ANALYSIS

For data collection, a web-based survey form using Microsoft Forms was created and sent to the willing participants with the following questions (as referred to and modified by Forbes et al., (2021)). Further, the last question was added to seek inputs on measures to be taken for accelerating lean implementation, considering the benefits of lean implementation.

How did your company get started with lean? And why?

How did you personally become involved with lean implementation?

How are you training your employees/subordinates? What do they read? What games/simulations do they play? Any other innovative way of training your employees?

How much time does your organisation devote to training employees for Lean? Is training a “one-time” or "recurring"?

To what extent do you train your trade partners (subcontractors/labourers/clients/suppliers/any other)? Who among your trade partners should be trained more and why?

Has lean been incorporated into your company's guiding principles/values/processes? If so, how?

Any other suggestions for accelerating lean implementation in India?

Regarding the academicians, the objective is to identify the teaching efforts in Lean construction. Therefore, the following questions were asked:

Students at which level (Undergraduate/postgraduate) you teach and at what level they should be taught Lean! Why?

What do the students read? What games/simulations do they play?

Any other suggestions for accelerating lean implementation in India?

A total of ten industry professionals and five academicians responded to the survey. The details of the respondents from the construction companies are provided in Table 1. The industry respondents' experience in lean ranges from 0.5 to 7 years, and their total experience ranges from 2 to 16 years.

Table 1: Details of the respondents from the industry

Company	Respondent Id	Designation	Work Experience (in Years)	Experience Practicing Lean (in Years)	Company Core Market	Company Type
A	1	Project Manager	13.0	0.5	Buildings	Owner/Client
B	2	Regional Lean Manager	8.0	7.0	Buildings, Malls, Airport	Consultant (PMC)
B	4	Planning Manager	16.0	4.0	Buildings	Consultant (PMC)
C	3	Planning Engineer	6.0	6.0	Infrastructure	Contractor
C	6	Senior Engineer	7.0	2.0	Infrastructure	Contractor
D	5	R&D Engineer	2.0	2.0	Infrastructure & Buildings	Contractor
E	7	Assistant Manager	5.5	1.5	Infrastructure	Contractor
E	8	Assistant Manager	7.5	2.0	Buildings	Contractor
E	9	Assistant Manager	4.5	1.0	Buildings	Contractor
F	10	Deputy Manager	2.0	2.0	Buildings	Contractor

Similarly, academicians' details are provided in Table 2, along with the institute they teach. The academicians are teaching lean construction from a minimum of 3 to a maximum of 10 years. Further, the academicians in the range of assistant professors, professors, and heads of the university, from four different institutions have provided the inputs for the survey. Further, in Table 3, the details of the case study companies are provided. It can be inferred that lean implementation started in 2008. The companies are long-standing, with more than fifty years of existence in the construction industry.

Table 2: Details of the respondents from the academia

Academia ID	Academia Type	Respondent	Designation	Overall Experience (in Years)	Experience in Teaching Lean (in Years)
Academia A	University	1	Professor	22.00	6.00
Academia B	Institute for Postgraduation	2	Professor	40.00	10.00
Academia B		3	Assistant Professor	14.00	3.00
Academia C	University	4	Head	35.00	10.00
Academia D	Engineering College	5	Assistant Professor	15.00	3.00

Table 3: Details of the Companies with Lean Implementation

Company	Company Category	Lean Implementation in India	Brief Description
A	Owner/Client	2022	Set up in 1953 as an infrastructure construction firm to undertake the construction of government projects. In 1986 the company diversified and ventured into private real estate development.
B	Consultant (PMC)	2007	100+ years old US-based construction company providing Project Management Consultant Services in India.
C	Contractor	2008	One of the well-known companies in the Infrastructure sector, namely, marine structures, surface transport, Oil& gas, hydro & underground, and urban infrastructure. Set up in 1959
D	Contractor	2013	It was started as a small contractor in 1956 to construct irrigation systems in southern India. In its 66 years, the company has grown in scale and strength, covering all infrastructure and residential projects in India.
E	Contractor	2008	Buildings vertical of a construction company founded in 1938, regarded as a professionally managed Indian multinational construction company engaged in Technology, Engineering, Construction, and Infrastructure Projects.
F	Contractor	2010	It was established in 1865, offering ‘turnkey solutions’, from ‘concept-to-commissioning’ across the entire spectrum of urban infrastructure.

EFFORTS OF CONSTRUCTION COMPANIES FOR LEAN IMPLEMENTATION

The case companies' lean implementation journey and the respondent answers based on the qualitative content analysis have been summarised in the below sections.

Lean journey commencement

The lean journey has begun in client organisation company A, aiming to increase productivity. The consultant organisation company B, being a US-based organisation, has lean in its operational standards. The operational standards provide standard work breakdown structure, procedures, workflows, and templates that standardise our work across projects and regions/countries.

The contracting organisations C, D, E, and F have different reasons for lean implementation. Company C has begun lean due to emphasis on early completion of the projects. The primary motivation for Company D to begin the lean journey is to get information transparency among stakeholders on the project's progress. Company E has targeted wastage reduction, rework and thus cost reduction, for which lean is being implemented at project sites. Company F adopted lean to reduce hidden costs and optimise the construction activities' timeline. Further, it is to be noted that ILCE has acted as a facilitator-cum-catalyst for lean implementation in the contractor companies, namely C, D, E and F. While companies C, E, and F are founding charter members of ILCE from 2008, Company D joined ILCE in 2013 as they became aware of lean construction through a professor at Indian Institute of Technology, Madras (IITM).

The reason for respondents' involvement in lean implementation is majorly the management decision and part of roles and responsibilities. However, there are a few exceptions. Respondents 8 and 9 from company E are selected for the company's Lean implementation program. The lean implementation process in company E is as follows: 1. Select a site for lean implementation, 2. Identify lean champion(s) in the specific site, 3. Provide the documents and access to the lean repository (use cases), 4. Be at the site for a week to check and correct the implementation, 5. Obtain weekly/monthly reports to see the improvement and benefits.

Respondent 10, from company F, is part of a lean journey because of doing the course on "Lean project delivery" during the postgraduation in construction management, and Respondent 5 has done the final year project on Lean Construction, which has fetched the role of "Lean Coordinator" at company D.

To summarise, motivation for lean implementation by case companies is to gain cost and time savings, and the driving force is top management. Further, lean tools used for productivity improvement, waste reduction, and increased transparency about the progress.

Lean training for the employees

Company A's training efforts are minimal as they are in the very early stage of lean implementation. Currently, only one training is conducted for two employees in LPS so that they can implement it. However, the company management plans to take up further training based on the success of LPS implementation.

Respondent 2 from company B was given stepwise training initially with an emphasis on what precisely lean is for commencing the journey with willingness. There are training modules for employees at basic and advanced levels. Further, company B has a University Knowledge Network for different sets of training conducted online and in person.

Company C uses Silent Squares simulation and E-Learning courses on Lean to train employees. Company E has two different training programs for Lean Champions and the project team separately and is provided at the start of lean implementation at a project level. The various tools and processes that have been fixed to be implemented are explained to the employees through these two training programs with the help of the company's case studies from other similar projects. Company F has engaged only selected employees with the National Programme on Technology Enhanced Learning (NPTEL) based Introduction to Lean Construction course conducted by Prof. Koshy Varghese and Prof. Raghavan N from IITM.

Compared to all the companies, Company D, though it started its lean journey in 2013, five years later than companies C, E, and F, has developed a specific training plan as follows:

employees take the NPTEL "Introduction to Lean Construction: Module 1 - Basics" course which is mandatory, followed by internal training with their Lean experts (employees whose experience in Lean implementation is more than five years) in a virtual mode with the help of presentations and case studies from the company project sites. Further, Company D has a "Villego" Simulation Kit, which was outsourced from "The Change Business- UK", a Lean Consultancy, for the Last Planner System.

Concerning the training frequency, the common aspect of all these companies is that the management encourages these employees to attend the training workshops and conferences held by ILCE. However, the in-house training frequency as per the respondents is based on the need of the hour at the site level rather than a recurring and scheduled event, except for company C where the training frequency is once a quarter for everyone. Further, as part of its lean implementation program, Company E imparts training whenever a new member joins the program.

Overall, the efforts on employee training towards Lean Construction differs for each company. Only one of the case companies has a defined training plan and one has defined training frequency whereas all others treat training employees as per the need of the hour.

Lean training for trade partners

The trade partners for the construction companies are trade partners (subcontractors, workers, clients, and suppliers. The training for the trade partners is significantly less across the companies. Companies A, C, and F currently do not have any training programs for trade partners. However, the respondent from company A feels that there should be a particular focus on training workers. The respondents from companies C and F believe sub-contractors are to be trained to introduce the benefits of implementing the lean.

Company B trains the trade partners, at-least on weekly mass training. Company D has yet to train the external project players (sub-contractors, clients, suppliers, and consultants). However, training the workers on Lean tools like 5S (Sort, Set in Order, Shine, Standardize, and Sustain) & 3P (Production Preparation Process) with sign boards in *their regional language*. Further, Company E trains the workers through the lean champions and site engineers involved in the specific activity in which lean is implemented. Further, the respondents from company E feel that all the workers, including subcontractor's supervisors, are to be trained, and even the material suppliers/ vendors should also be provided virtual training as they do not visit the site.

As the current training efforts are targeting internal employees, training trade partners is limited. At this juncture, the respondents opine that subcontractor supervisors, subcontractors, and workers are to be imparted lean training for maximising the benefits.

The Lean as part of the organisation's guiding principles/values/processes

The company's approach to adding lean to the existing systems is different. Company E has incorporated lean management as a section in the project quality plan (PQP), which makes adopting tools and practices an auditable point. Moreover, this enables the project teams to adopt these practices. At Company C, mainly 5S, root cause analysis (RCA), LPS and Value Stream Mapping (VSM) are strictly implemented at construction sites to improve project activities continuously. Company D has done mandatory training for all employees on Lean construction with a well-defined training plan.

Further, Company D has made Lean implementation one of the key results indicators (KRI) of the employee performance appraisal system. Further, Company F has incorporated LPS as an integrated part of IMS (Integrated Management System) processes. Company B has incorporated the pre-construction phase as part of the project management plan so that the implementation during the construction phase can be made easy and handy. Company A, being in the initial stages of implementation, has yet to plan for now but is interested in adding it to the company's process, provided LPS implementation is successful.

The approach to incorporate Lean into company's existing policies is different by the companies. Each have chosen a different approach as explained above. However, it is interesting to note that Lean is being injected into the companies existing process one way or other. Table 4 provides the summary of the lean implementation, teaching and training efforts, ways of introducing into companies existing process illustrating the similarities and differences across the companies.

Table 4: Summary of Training Efforts of the Construction companies

Company	A (Client)	B (Consultant)	C (Contractor)	D (Contractor)	E (Contractor)	F (Contractor)
Company Lean journey	Productivity improveme nt	Operational standard	Early completion	Information transparen cy on project progress	Wastage and rework reduction	Hidden costs reduction and optimising time
Respond ent's lean journey	Manageme nt decision	Part of the Roles and Responsibili ty-ty	Manageme nt decision	Project work on Lean Constructio n-n	Lean Implementati on team	Course on Lean project delivery
Training employe-es	Very limited training so far	Corporate university – basic and advanced levels	Silent Squares simulation and E-Learning courses	Well-defined mandatory training plan & Villego	Two programs – for Lean champions and the Project team at the start of the project	NPTEL course for the selected employee
Time devoted to training	Nil	Need basis	Quarterly	Need basis	Need basis	Need basis
Trade partners trained	None	Mass training for all trade partners	None	Workmen	Workmen	None
Lean in Company processe -s	None	Project managemen t-t Plan	5S, VSM, RCA, LPS mandatory	Mandatory training and lean implementa tion as KRI	Project Quality Plan for Audit	LPS as part of IMS

EFFORTS OF ACADEMIA FOR LEAN TEACHING

The respondents representing the four academic institutions have provided their inputs on how they have been contributing to the lean implementation, and the summary of the teaching efforts, and the resources used for teaching are provided in the sections below.

Lean teaching for students

The students at Academia A are being taught at the postgraduate level with a subject titled "Lean Construction". Further, the course is being delivered as an elective, which the students choose. However, the respondent from Academia A feels the course could be introduced as a higher-level elective at the final year undergraduate level. Moreover, the university has made a collaboration with UK based university for a project titled Collaborative Online International Learning (COIL) project to create awareness about lean and sustainability. Similarly, Academia B also offers a course on Lean construction at the postgraduate level, except that it plans to make it a core/compulsory course.

Academia C offers courses in the built environment. The builders/developer organisations have been provided with training on saving materials and time costs. In this process, the institute started adding topics on lean construction, which the builders/developer organisations accepted well. Therefore, Academia C has been teaching lean construction practices as an elective in two of their master of business administration programmes for the last five years. Academia D offers all engineering courses. However, the institute has started offering specialisation in Lean Construction Technology as part of the graduate-level civil engineering course. The Lean construction courses are delivered in the third and final year of the bachelor of engineering course.

One out of the case academic institutions has introduced Lean Construction at the undergraduate level, whereas rest of the institutions have been teaching at the postgraduate level. Further, the course at postgraduate level is being offered as an elective as an alternative construction project management method.

Resources used for Lean teaching

Training the students at academia A and B is based on the concepts in the textbooks on lean, journal papers or online material. Further, games involving card games, aeroplane games, and pattern development games are used for teaching Lean Construction. Occasionally role-play games are used to simulate the construction scenarios. At Academia B, the students are given lean concept theory linked with practical application through case studies. Further, Academia A and B have hosted ILCC conferences and engaged students as volunteers, encouraging them to see the practical application of Lean Construction. Multiple lean awareness exposure games and lean software are used to train and teach the students at Academia C.

Overall, games, books, journals and case studies are major part of the resources used for teaching.

SUGGESTED MEASURES FOR ACCELERATING LEAN IMPLEMENTATION IN INDIA

Lean was introduced to India fifteen years back by IITM and ILCE in 2008-2009 (Raghavan et al., 2014). However, the number of contracting parties reporting lean implementation is less compared to the number of construction companies in India. Considering the advances in technology adoption requirements, there is a need to fast-track the lean implementation (ILCE (n.d)). Therefore, the respondents, being lean trainers and lean implementers, were asked to provide their suggestions for accelerating lean implementation in India.

The measures suggested by the respondents are: 1. Marketing in the industry by showcasing the success stories and their positive outcomes with the Tier II & Tier III contractors, 2. Devising Lean construction-based courses jointly by construction companies and educational Institutes, 3. Integrated Project Delivery (IPD) or Relational contracting approach for construction project delivery. 4. Engaging with public policy decision-making authorities more frequently for mandating Lean Construction - Introducing lean implementation as a prequalification criterion, 5. Improve Lean knowledge and awareness of clients in India, 6. Introduction of the lean rating and lean certification, 7. Sharing of incentives with the trade partners for promoting lean adoption, 8. Increasing the training of frontline workers and supervisors, and 9. Use of computer simulations to enable the selection of lean tools for better decision-making and implementation. Further, majority of these measures are considered as enablers of lean construction (Bayhan et al., 2019 & Moradi, Sormunen 2013)

In this context, the role of organisations is crucial for conducting specific training dedicated workshops and monitoring their incremental progress over a period. ILCE has been connecting the industry and academia by conducting ILCC conferences at the academic institutes to promote Lean in India. Further, academia should also bring in a compulsory course (rather than as an elective) on lean construction in undergraduate and postgraduate courses for all disciplines, so that lean awareness is ensured at the entry level of the construction industry.

CONCLUSIONS

The study has used multiple research methods to understand the efforts of industry and academia towards lean education and training in India. A total of fifteen respondents from six companies and four educational institutes have provided valuable inputs on how lean is being implemented and the training and teaching efforts. It has been observed that the primary motive for lean implementation is to get cost and time savings, and the top management is driving the lean implementation. Therefore, creating further awareness and marketing Lean should attract more construction companies to adopt lean.

The company's approach towards implementing Lean in existing company procedures is varied. However, all the approaches presented in this study can be referred to by the companies in developing countries and adapt to which one best fits their organisational setup. Further, the true success of Lean implementation is possible only when there is a significant cultural change brought among all the project stakeholders, focusing on suppliers/vendors, subcontractor supervisors, and frontline workers.

There is a need to show the clients the potential benefits of Lean by contractors and advocate implementation beyond contractual obligations. It would eventually have significant benefits for all the stakeholders in the Construction Ecosystem. The research is helpful to both researchers and practitioners to gain further insights on lean implementation and teaching/training in India and is a source of information for the potential construction companies wishing to implement Lean construction.

LIMITATIONS AND FUTURE WORK

The number of respondents from each company/institute is limited. There could be construction companies not presenting at the conferences, not joining the ILCE, but implementing Lean on a full scale. Therefore, a survey of nationwide construction companies will facilitate further understanding. While the research has obtained data saturation representing each organisation, increasing the number of respondents from each organisation, conducting qualitative interviews, and longitudinal studies would provide further insights into the teaching and training efforts and validate the suggested measures for accelerating lean implementation in India.

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HOW TO NAVIGATE THE DILEMMA OF VALUE DELIVERY: A VALUE IDENTIFICATION GAME

Salam Khalife[1] and Farook Hamzeh[2]

ABSTRACT

Delivering value on projects is one of the fundamental concepts in lean construction through the Transformation-Flow-Value (TFV) theory. The concepts of transformation and flow are thoroughly explained through the lean construction literature, and various educational games are offered to support the understanding of the flow concept including work-flow variability, takt time, waste elimination, pull systems, and efficient planning. The concept of value, however, tends to be more complicated where researchers are continuously trying to better understand value delivery on construction projects. The International Group for Lean Construction conference offered research on Target Value Design as well as games to reap knowledge about project value. This paper provides additional support to understand the value concept and its characteristics through a proposed educational simulation game. The game demonstrates how designers identify requirements on projects, how various parties value different things, and how to potentially deal with conflicting requirements. The game helps students and lean practitioners in understanding the process of eliciting perceived value on a project and achieving shared understanding through proper communication between different parties. This would help in managing projects in a way that delivers higher value for the different stakeholders, thus achieving successful projects with higher satisfaction rates.

KEYWORDS

Value and design management, serious games simulations, collaboration, benefits realization.

INTRODUCTION

The early definition of value in construction has focused on understanding and achieving client's needs or client's objectives (Bertelsen & Emmitt, 2005). However, different stakeholders on a project have their own interests and needs, thus formulating a different value perception (Haddadi et al., 2016). Accordingly, research had looked into separating the value of interests into external and internal value (Emmitt et al., 2005). External value represents the client value, and internal value is defined by and between the design and delivery team (Emmitt et al., 2005). Additionally, the client in this case represents different stakeholders including the users of the building, the owner, and investors. Not to forget, the surrounding neighbourhood and community needs are part of the client's complex system. Given this complexity, it is difficult to conceptualize and define value. User's and owner's value must be aligned and the design team shall need effective processes to create value on projects (Haddadi et al., 2016).

Moreover, value on projects has distinct characteristics being dynamic or changing over time, subjective, and stakeholder specific (Christoffersen, 2003). Regarding the latter,

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conflicting requirements among stakeholders on projects is a major issue when delivering value. Drevland et al. (2017) discussed ethical dilemmas when delivering value on projects, where questions on whose value to prioritize "the good of the client versus the good of wider society" or "the good of the developer versus the good of the buyer". Thus, this adds up to value complexity and confusion. Accordingly, research is still investigating ways to simplify the concept and propose methods and tools to understand how to deliver value on projects.

The problem amplifies when talking about novice lean practitioners and designers. They usually do not have a clear idea about the concept of delivering value on projects nor the complexity of the design process, specifically the early ideation phase. In an attempt to help resolve this issue, and to provide a clearer picture of the value concept, this research adopted the active learning path by proposing a value identification educational game. Target Value Design (TVD) games have been proven to be effective in learning important principles relating to TVD and improving overall value while considering a target cost (Jacob et al., 2021). Such games has been proven to act as useful pedagogical techniques to teach challenging concepts in lean construction while increasing students' enthusiasm (Hamzeh et al., 2017). A growing use of these games have been identified using a systematic review conducted by Bhatnagar et al. (2022) proving their effectiveness. In this study, 96 lean games were identified and only one game relates to value capture and value management (beyond TVD games) and this game was categorized as slightly discussed. While the concept of value is still considered vague, this suggests that there is a need for such research to help in better understanding value and consequently delivering it and achieving higher satisfaction on projects. This paper contributes to the growing field of using simulation games as tools for learning lean concepts by specifically focusing on the value identification component. Achieving a better understanding of the ambiguities inherent in our concepts of project value can provide an opportunity for achieving higher value.

THE VALUE CONCEPT

VALUE DISCUSSIONS IN THE LEAN COMMUNITY

The international lean community has been involved in research about value delivery since the inception of the lean construction group. From the early start of lean philosophy, Koskela (1996) admitted that practitioners do not really understand how value is generated during a project and called for challenging theoretical research. Customers have expectations and requirements, and designers or suppliers would need to provide value through their product or services. Yet Koskela (1996) described the internal mechanism of this two-way connection as a black box. Ballard & Howell (1998) explained how thinking about value alters the traditional conversion model in design which requests the customer to clearly present their complete or fixed design brief. Contrary to that, designers need to elicit customer's desires, explain their consequences, and negotiate customer's ends and means (Ballard & Howell, 1998). Additionally, Leinonen & Huovila (2000) in their paper *the House of the Rising Value,* they indicated the difficulty, yet the importance, of creating value. They suggested in their study a tool that provides realization of project performance based on project definition. It can be combined with quality function deployment tool which helps creates requirements from needs. The paper highlighted that methods to enhance value creation are available but still not fully exploited and difficult to deal with.

Since then, researchers invested time and efforts to assist the construction industry in general and the lean community specifically with finding answers and improving knowledge about the value concept and associated methods.

In fact, from the repository of the IGLC conference, for the years between 1996 and 2021, more than forty papers are categorized under the *value generation* topic providing insights and research evolution on the value topic. Salvatierra-Garrido et al. (2012) performed a literature review to explore the value concept within the IGLC conference proceedings from years 1993 till 2011. They spotted that the value concept is still ambiguous due to the various interpretations of its meaning and due to its subjective nature. Also, the research noticed the focus on delivering value at the project construction level by reducing waste and praised the efforts to fulfil customer's requirements.

In general, going through a good deal of the lean construction literature, the following approaches were offered as basis for identifying and improving value on projects:

- Collaboration as basis for project delivery: collaborative decision-making, early involvement of downstream players in design, intensified planning, and open communication to produce a clear brief.
- Cross-disciplinary coordination and intensified design with multiple professionals.
- Co-location; productive work environment: specifying the right pace, meeting frequency, meeting agendas, interactive design sessions, big room with right people, freely share concepts and ideas.
- Bring problems to surface, have candid conversations, and proactively change course of action.
- Carefully selecting teams: based on mindset and alignments, based on prequalification.

The proposed value identification game focuses on the first point and intends to provide assistant with producing the value proposition list (also called the value attributes list).

WHY LEARNING ABOUT PROJECT VALUE IS IMPORTANT

Researchers and practitioners have expressed interest in learning about the concept of delivering value on projects as indicated above. The lean community had offered a specific category in the international group of lean construction conference named *Value generation*, which reflects the importance of investigating the topic beyond making it merely about project construction processes and minimizing waste. The briefing process still suffers from unstructured methods (Leinonen & Huovila, 2000), therefore learning about value identification would help in structuring the briefing exercise more. Moreover, during the lean course, as soon as the educator reaches sessions about early design phases and the wicked design process, confusion is noticed. The silent squares game helps students learn about the importance of collaboration to minimize rework in design. Yet, focusing on the value identification is still needed.

In the business world, a value proposition canvas had been introduced to produce products that meet customers' needs by understanding their problems. Construction projects are no different. Architecture and engineering professionals need to produce projects that meet different stakeholder's needs including those of the customers, end-users, and communities (Pirozzi, 2019). Learning about the value concepts and how to identify value from the early beginning will help practitioners in minimizing iterations in design. Nonetheless, designers need to keep their options open. This is called Set-based design in lean, and part of it is related to delivering higher value by keeping flexibility and not locking design early during the project design (Ballard, 2000). We are trying to focus on the fact that design is not a onetime *shot*, design evolves as needs also evolve with the progression of the project. Design thinking is a problem-solving approach used to create design solutions that focus on user's needs. It involves several steps to reach a satisfactory design solution including: empathy, ideation to generate a wide range of ideas by brainstorming, defining, prototyping, divergence and convergence, then testing to refine the solution based on feedback (Efeoglu et al., 2013). Identifying value relates to the first two steps of the design thinking approach.

Moreover, learning about project value will help in understanding that hidden needs exist. Wandahl (2004) explained the four windows for requirements and needs on projects (Figure 1). The first includes what is known for both the client and the design/delivery team. The second is what is not known to the client but know to the team. The team in this case helps the client by asking questions and making requirements clear. The third window includes what is known to the client but not known to the team. Here, the client should inform the team about their desires and expectation by simply telling them. The hardest part is window four where requirements are unknown for both the client and the team. It takes a lot of collaboration on projects through workshops, questions, researching, and transparent engagement to try to reveal those hidden needs.

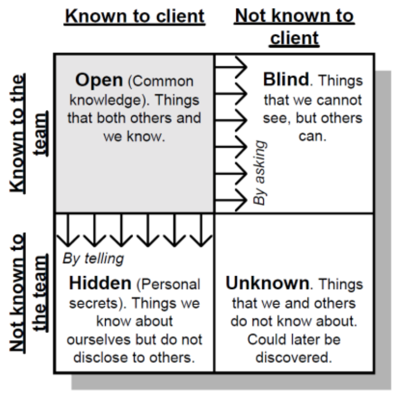

Figure 1: Johari Window retrieved from (Wandahl, 2004).

THE VALUE IDENTIFICATION GAME

GAME DEVELOPMENT AND LEARNING OBJECTIVES

The authors developed the value identification game or Value ID game to help novice designers and project managers in understanding the concept and the process of identifying value on construction projects. This preliminary step of identifying value would help in subsequently delivering higher value during the project phases. One of the authors has been teaching lean construction for more than ten years now and the value topic always raised curiosity among students. The idea of developing this game was thus inspired in the classroom. Yet, the actual development of the game was when the authors got involved in the design of a housing project and sensed the confusion among practitioners as well regarding dealing with requirements and value identification. The game was then developed and tested in a class setting a few times and then presented in front of lean experts to get feedback. The adjustments in the game based on feedback are specified in the relevant sections herein.

Thus, questions about project ideation and value definition were raised; How to identify owner's needs? Users' needs? Community's social needs? Environmental needs? How to make these needs work in conjunction with each other? How to deal with conflicting requirements? And how to really understand what is behind the client's requirements? The design production is related to storytelling, designers need to elicit the needs of different parties, research the different alternatives and options, and then innovate to uniquely produce the preferred design. In response to these inquires and to understand the general idea of value identification, the authors proposed this game to facilitate drawing connections to the importance of understanding value and having a clear vision from the beginning. Specifically, the authors highlight the three main learning objectives of this game:

- Learning Obj.#1: Deepen knowledge of the value identification concept and value characteristics on construction projects.
- Learning Obj. #2: Augment understanding of project owners as a system and that the system has many and varied statements of value that might include conflicting requirements on projects.

- Learning Obj.#3: Gain the ability to communicate efficiently and come up with proper questions to elicit information from project owners and customers.

Additionally, after playing the game, participants should be able to (Learning outcomes):

- Learning outcome #1: Identify value propositions on a project based on project goals and client's needs and translate them into design solutions/criteria.
- Learning outcome #2: Evaluate different design alternative against the value propositions.

The following sections explain the game rules and roles. Then later in the paper, the discussion section will relate between the mentioned learning objectives and outcomes and the results of the game.

GAME ROLES, RULES, AND THE STORY

The game includes four steps. In the first step, the game facilitator invites students to team up and form a design team of 4-5 people. We ask participants to select different roles: one to two architects, one structural/civil engineer, one electromechanical engineer (MEP) and a contractor. Based on their background, they need to provide suggestions about the general design. But first, the facilitator needs to present to participants a script that includes a general description of the owner's vision – and end-users' preference if applicable – about the project. This script acts as the design brief for the project. In our case, we opted to experience the game on a two-floor private villa. The owner, which is basically the end-user in this case, offered their vision of the project. The owner submitted a short design brief, and we shared it with participants during the two trials. The text reads as follows: "*The house is located in a mountainous area facing the ocean. The owner is interested in sustainable designs and solutions. The owner has a lean thinking background. The owner would like to connect with nature. The owner has a tight budget.*" We mentioned that the 'owner has a good position in society'.

Next, the facilitator asks participants to discuss with their team what is considered of value for the project based on the description of owner's requirements or the general vision provided. In other words, the participants need to come up with suggestions of how the brief description could be translated into value propositions and design requirements. Each team should agree on the top five value criteria that need to be achieved during the design to have a project compatible with the client's vision. The team shall write the five design value criteria on the evaluation card provided – or in the google sheet provided (Figure 1). It is important that the facilitator recommends that participant be specific when listing the value criteria. As a modification, and based on the two trials we conducted, we suggest adding another column and splitting the brainstormed ideas into value propositions and design specification. The design specifications are translation of the value propositions. The team converts these value propositions into design solutions or technical solutions. For instance, a value proposition can be having natural light as a way to connect to nature, then the design solution related to this value could be designing large windows. When participants start to list the value propositions and the translated design solution, they would come across conflicting requirements. Going back to the example, having large windows to connect with nature will not be specifically sustainable since it would lead to pressure on the heating and cooling systems. The participants will need to figure out how to better resolve the conflicting design solutions through alternative design ideas.

Value Identification Game (V.ID) - Evaluation Sheet — *Group 1*

Design Criteria - Group A

	Step 1- Fill in the selected Design Value Criteria	Design Option 1	Design Option 2	Design Option 3
1	Natural material	7	10	10
2	color of material	4	9	10
3	use of glass for having nice view	8	8	10
4	use of solar power	1	8	9
5	Cost Effecient	5	7	8
	Total Grade	25	42	47

Step 2 -Evaluate options based on the criteria
Grade each design from 1-10

NOTES

Figure 2: Value Identification Card (Google sheets)

In the second step, the facilitator presents three design options for the suggested villa. Each team will need to evaluate the design options against their list of design value criteria. The scale used was 1-10, where 1 indicates the presented design option poorly reflects the design value criteria and 10 represents an extremely compatible design with the listed criteria. The team calculates the total score per design option out of 50, which is the sum of the grade number given for each of the criteria. The three options need to have a similar representation, so all three designs need to be presented in 2D and 3D. Preferably, the north side shall be revealed beside the plans as this would help in deciding about sustainability and energy-related concerns. A sample illustration for the three options is presented in Figure 3. The samples were collected from *pinterest.com* website. The purpose of these samples is to give an idea of what might be a good fit for the game. Any design would do, the important thing to keep in mind again is the story behind these designs and how to conduct the discussions after receiving the evaluations.

Option 1 | Option 2 | Option 3

Figure 3: Sample Illustration of the Design Options (not to scale)

In the third step, the facilitator elicits the scores per design option from each team. One representative from each team shall give an overview of the brainstorming process that helped in developing the value criteria based on the design brief. Afterwards, in step four, the facilitator will ask some questions to open a discussion and will need to talk about the story behind this exercise.

The discussion shall include two questions: (a) What did you notice during the teams' discussions on value identification and scoring the different options? And (b) what are some efficient ways that might improve the process of identifying value, revealing hidden needs, and improving satisfaction on projects? These two questions can generate ideas, specifically regarding collaboration among the different design disciplines and asking the right questions to reveal needs and design style.

As for the story behind this exercise and the design options, the facilitator shall explain that the options are design alternatives for the same project and were done in chronological order. Option one was the first design the architect provided to the client. The architect assumed that given the client's position in society, they would want a luxurious villa. The architect explained that the material used could be affordable to minimize cost. The architect wanted to impress the client. Therefore, option one needs to be the wildest. Obviously, this design option will still be over budget and does not match the lean thinking the client has. At this point, the client did not know what exactly the alternative should be but indicated that a simple design would do. Then, option 2 would be suggested. The design is now simple with huge windows opening to enjoy the mountainous views. The client realized one problem with this design which is the absence of balconies and terraces on the upper level. The design also would be costly for the heating and cooling systems. Thus, the designer reimagined the project as depicted in option 3, where balconies and windows with louvers were provided.

CLASSROOM SIMULATION

The first run of the proposed game was conducted by the authors as a simulation exercise in a lean construction graduate class at the University of Alberta. The selected project for this first trial was a real case study the authors were involved in. The options were the actual design alternatives. The four steps explained earlier were conducted.

After the teams were done with listing value propositions, rating the options, and discussing their thoughts, the authors explained that these options are design alternatives for the same project and read out the story. This was the AHA moment for the students. It was then clear for them that iterations in design are inevitable, yet to reduce these, design teams need to conduct deep conversations with the owner and collaborate early on the project. The authors then explained about the value concept and how to reach a shared understanding of what is of value on projects.

Students Input

We invited students to engage in discussions based on multiple questions after the game concluded. One question asked students to congregate a value criterion that they perceived as the owner's hidden value (implicit need) and explain their selection. This triggered a discussion about the meaning of hidden needs or implicit value criteria. It was confusing to students at first, but the authors explained that the more questions the design team asks, the more implicit needs are revealed. We usually refer to the design thinking bootcamp from Stanford, indicating "*Engaging with people directly reveals a tremendous amount about the way they think and the values they hold. Sometimes these thoughts and values are not obvious to the people who hold them. A deep engagement can surprise both the designer and the designee by the unanticipated insights that are different from what they actually do - are strong indicators of their deeply held beliefs about the way the world is."*(Plattner, 2010).

Another question was raised and intended to gather strategies that students think are important for understanding the clients' requirements and enhance delivering value on projects. Responses included:

- Early involvement of different design professionals and contractors
- Open communication and collaboration
- Ongoing open discussions; pick owner's brain
- The use of visuals and providing sample design styles

Finally, the authors asked students what were some characteristics of value that they might have picked up from this exercise. In this discussion we highlighted the dynamic nature of value where designers need to keep in touch with the owner/end-users and update them on the progress as some needs develop with the proliferation of more information (Khalife & Hamzeh, 2019).

LEAN CONSTRUCTION EXPERTS' SIMULATION

The authors presented and played the value identification simulation game with a group of lean experts and enthusiasts to further test the effectiveness of the developed game. This group gathers monthly for the purpose of testing and playing educational simulation games related to lean concepts under the name APLSO: Administering and Playing Lean Simulation On-line. The advantage of playing the game with this group is conducting a plus-delta session after the game to highlight the advantages and the deltas or areas that need improvement. These are highlighted in Table 1. More deltas were recorded but were not mentioned because they are already incorporated into the game, examples: consider putting everything in the same level of presentation, include a 3D perspective with all options, and include roles for the team members.

Table 1: Pluses and Deltas on the value game received from the APLSO Group

Pluses	Deltas
Original game design	1. Add cost/ influence graph?
Like the story behind it	2. Cost is not a criterion, but a constraint; so best not to include this as a criterion or it will create confusion in the lean community.
Liked the lesson behind it- owners need some input from designers to learn what they want	3. Owner has information and designer has missing information; therefore, need to build a bridge between the two; example: have a table with both their input
The game generated good discussion	4. Need two groups: tangible versus intangible
Different team members have different perspectives	5. More information on the site and energy efficiency/ mechanical systems

About the deltas, the points one and two answer each other. During the discussions, one of the attendees suggested adding cost or influence graph to the options, yet another participant from the lean experts said that cost should not be a criterion. If the game included cost, mostly participants will focus on that as the basis for their decision among options, therefore it was not logical to include it. Delta 3 cannot be incorporated because the goal of this exercise is to get the design team to discuss more with the limited information at hand. For delta 4, it would be hard to make one group focus only on the intangibles. In the end even intangible value criteria need to be translated to tangible design solutions. That is why we suggested splitting evaluation card into value propositions and design solutions. As for delta 5, this might be a good suggestion for future trial and implementation. The authors could add few information without being very specific so participants would not get affected by comparing numbers.

DISCUSSION

The value identification game is meant to be part of the lean simulation games that help in teaching lean concepts. The value concept is part of the wicked problems in the project definition phase, where wicked problems in design are associated with stakeholder needs and values (Whelton & Ballard, 2002). Therefore, to help students in understanding the value concept and the associated hurdle with identifying stakeholders needs, the value identification game is proposed. Based on two trials and feedback from lean experts and practitioners, the game was modified and presented. In this discussion part, the authors highlight the common points identified from the game trial discussions:

- At the start of the game, there was still a misunderstanding of how to translate the requirements into value propositions. After the discussions, participants had the AHA moment.
- The design brief is considered a mechanical outcome, we would rather want a value outcome on projects where human-centred design is essentially the target.
- Team alignment is part of the project value concept, where teams needed to collaboratively agree and brainstorm ideas in this game. People not agreeing on value definition is already value loss on projects.
- The more in-depth discussions took place, the more ideas were generated. Collaboration is the key.
- Players go through definition, development, negotiation, evaluation, so they move from the value definition to value alignment phase, then later value delivery can take place.
- Designers need to avoid projecting personal thoughts; instead, designers need to coordinate their perception of design.
- Participants need to clarify the tangibles that reflect the value propositions, since the only thing provided to them is the design of the house without any further input from the owner.
- In reference to the Johari window, the game focuses on the third quadrant and touch base on the fourth. The participants will be trying through this game to extract more information based on the available description. It is good to include the Johari window at the end so participants can relate to what they are doing in the game.

To sum up the take-aways from the game, Figure 4 is provided as part of the presentation that the facilitator could provide participants with by the end of the game.

Figure 4: Value take-aways from the Game.

Finally, based on the discussions in the two trials, the authors could assess that the learning objectives were met. Participants had gained more knowledge about the value identification exercise after the game, and they learned about the value being dynamic from the story behind this game. Participants also came across conflicting requirements. The facilitator highlighted the need to ask questions and collaborate to elicit more information than what is provided usually by owners and participants learned about this strategy. It might be relevant to mention the design thinking approach and human-centered design with this game. Design thinking is known for investigating human needs, scoping, defining the problem at hand, personas understanding, user experience mapping and more. The game relates to the first two stages of design thinking: empathize and define. Emphasize is where the designer sees the world from the user's perspective, understands their feelings and motivation, and communicates their understanding. Define stage is where the designer collects ideas to present functions needed to solve problem at hand, similar to the approach in the game. Therefore, mentioning design thinking helps in establishing the connection and explaining that value needs to be delivered in any product not only construction projects.

CONCLUSIONS & FUTURE DIRECTION

This paper proposes a value identification game to help students and novice practitioners in understanding the concept of value and learn to define value propositions through interactive means and observations of different viewpoints. The game includes four steps starting with brainstorming ideas to elicit what is important on the project given the project brief and listing them as value criteria and design solutions. The team of different disciplines will need to coordinate and discuss if there are conflicting requirements identified. Then, the facilitator will provide 3 design options and ask the team to evaluate these against the value criteria listed. In step three, the different teams share ideas and see which option got higher scores. Step four constitutes the main discussion, where the facilitator tells the story behind the games and the options provided and asks provocative questions. Participants will learn that projects normally comprise conflicting requirements, which means they need to deal with these and be informed about the strategies to mitigate the conflicts. Through this game, the authors highlight the issue of hidden needs and the dynamic nature of customers' requirements and the value they perceive of the project. Collaboration and team alignment are also important takeaways from the game. Open candid conversations need to take place because even knowledgeable owners take time into the process to figure out their needs. This idea is often overlooked, and owners are expected to express their need upfront in the design.

After conducting the game in a graduate class setting and with lean experts, positive feedback was received, and possible future additions can be considered. On a final note, the authors had come across the recent trend in design. Artificial intelligence has found its way into developing design concepts using AI art generators. Recently, we have been witnessing design engines that use AI to generate design photos based on a set of words that describe the project. It kind of resembles the current game setting, where the design team are requested to filter out the design options based on the set of value attributes or value propositions inspired from the brief. A future version might be considered which includes comparing the effect of these AI generators and their adaptability to generate design solutions based on the keywords being the top value attributes identified.

Finally, lean philosophy has people at its heart. Value is deeply correlated with social impact, social justice, and equitable living. The game could be tailored to reveal such important ideas. The game conductor may opt to provide a hospital project as an example, or an elderly care center, or a rehabilitation center. The authors believe in visuals and interactions to highlight important ideas in connection with delivering value on projects.

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DEVELOPMENT AND TESTING OF A DIGITAL LEAN TOOL TO SHARPEN MOTION AND TRANSPORTATION WASTE RECOGNITION

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ABSTRACT

There is a need to create ways to communicate opportunities for motion and transportation waste reduction and productivity enhancement that align with the visual management characteristics of those practicing within the construction industry. In this study, researchers aimed to evaluate the effectiveness of an interactive online simulation game that generates spaghetti diagrams as a tool for improving conceptual understanding of motion and transportation waste reduction, that could potentially be used by lean educators in the construction industry. The tool was developed using Unity™ and tested against a control group. To ensure the concept was relatable to participants across different roles, the commonly experienced activity of making spaghetti was chosen as the simulation scenario. Participant feedback from preliminary testing of the online simulation game indicated that the activity was enjoyable and appeared to heighten participant awareness of object placement. Metrics generated by the simulation—as well as post-play discussion—appeared to help participants perceive how elimination of motion and transportation waste can potentially improve their performance. The intent of the simulation is to spur post-simulation discussion with participants about identifying and reducing waste in their own varied processes such as job site operations and procurement.

KEYWORDS

Motion Waste, Transportation Waste, Lean Simulation, Lean Construction, Online Game, Serious Games, Spaghetti Diagram, Productivity Awareness

INTRODUCTION

Simulation games can be used in the classroom to promote learning, facilitate classroom instruction, and boost comprehension among students (Bhatnagar et al., 2022; Hamzeh et al., 2017). Furthermore, students expect university education to be entertaining and simulation games can impart learning in an enjoyable way (Kapp, 2012; Prensky, 2007).

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A review of relevant literature suggests that a spaghetti diagram is a potentially impactful tool that can help reduce unnecessary movements. Kanaganayagam (2015) describes a spaghetti diagram as a method of visualizing the path of movement of an actor or object using a line. By identifying motion and transportation waste, spaghetti diagrams help organizations reduce superfluous labor and implement changes to organizational structure or workstation layouts (Senderska et al., 2017). Spaghetti diagrams are powerful tools to identify and reduce unnecessary motions. However, a major drawback is that traditional spaghetti diagrams are static and time-consuming to create, limiting their usefulness for dynamic environments such as construction sites. While vision-based approaches allow for real-time monitoring, they do not currently offer the ability to quickly generate spaghetti diagrams to visualize motion waste. This presents a significant opportunity for the construction industry to improve their processes by leveraging the potential of rapidly generated spaghetti diagrams. This research proposes that an online game generating spaghetti diagrams can potentially enhance the performance of the construction industry by presenting visual opportunities for reducing waste and improving productivity.

EXPERIENTIAL LEARNING AND SERIOUS GAMES

Experiential Learning, often referred to as involved, evidential, or situational learning, is a participatory, interactive, and practical style of learning (Hawtrey, 2007). It permits environmental interaction and exposure to varied and unpredictable processes (Gentry, 1990).

Experiential learning, in its more advanced forms, provides possibilities for "data learning" by requiring students to actively participate in the learning process and to engage in expression of their ideas, utilization of inductive reasoning, or collaboration within groups. In fact, when a participant transitions from the role of a passive listener to an active respondent, this process is known as experiential learning (Hawtrey, 2007).

This research is focused on game-based learning which is aligned with experiential learning. The serious game movement is a response to the need to combine play and meaningful content with advanced capabilities (Spires, 2008). Games in this category incorporate social themes or problems into the gameplay, giving players a fresh viewpoint through active participation (Johnson et al., 2012).

Several studies, including Cassidy (2003), Sacks et al. (2007), and Tommelein et al. (1999), have demonstrated that computer simulations can be more effective than traditional methods of instruction. However, to ensure effectiveness, it is essential to develop a user-friendly design with clear instructions and graphics which illustrate that which is to learned (Gadre et al., 2011; Kuriger et al., 2010). Additionally, feedback is critical for knowledge and skill improvement. Without accurate feedback, learners cannot draw reliable conclusions about that which have learned (Gentry, 1990).

SIMULATIONS AND GAMES IN LEAN EDUCATION

Lean philosophy has given rise to principles and a set of tools to help identify and eliminate waste embedded within processes through the practice of continuous improvement. Elimination of waste, addition of value, continuous improvement, and a culture of respect are the four cornerstones of Lean philosophy (Rybkowski et al., 2018). Although they were arguably built upon productivity theories from Frederick Taylor, Frank and Lillian Gilbreth, and W. Edwards Deming, among others, lean concepts are often summarized as part of The Toyota Production System (TPS). Koskela (2000) is credited with being among the first to apply Lean principles to the construction industry.

A central notion in Lean is waste reduction, which Toyota defines as "anything other than the absolute minimum quantity of materials, equipment, and labor required to add value to the product" (Alarcon, 1997, p. 1). Many authors define lean as a technique for reducing waste.

However, others have argued the actual purpose of reducing waste is to free up resources to enable maximizing value (Sundar et al., 2014). While others have since argued there are additional wastes, Taiichi Ohno originally listed seven: overproduction, time on hand, transportation, processing itself (e.g. overprocessing), stock on hand, movement (i.e. motion), and defective goods. Ohno contended that getting rid of these wastes would lower production costs and boost profits (Ohno, 1988).

Building operations can be optimized using Lean waste elimination principles and analysis of value-adding and non-value-adding activities. Simulation games can serve as a valuable tool to teach these principles and tap into Lean's potential in the field of construction and its business operations (Bhatnagar & Devkar, 2021).

Although Lean concepts such as flow, value, waste reduction, and value maximization are promising and have the potential to improve construction processes, a literature review suggests that the complexity of Lean philosophy and a lack of knowledge about Lean are considered potential barriers to the adoption of its principles in the construction industry (Demirkesen et al., 2019).

Simulation games provide a unique opportunity for hands-on learning, effectively bridging the gap between theoretical knowledge and practical applications in Lean philosophy. In fact, Lean pioneers Greg Howell and Glenn Ballard began experimenting with Lean Construction simulations as early as the 1980s. Simulation games have traditionally been utilized to teach outsiders about Lean building practices and processes, and have proven to be a valuable tool for promoting understanding and engagement with Lean concepts (Tsao & Howell, 2015).

Simulation games provide a dynamic and error-free learning environment that allows individuals to gain a deeper understanding of Lean principles through hands-on experience. By providing a realistic simulation of real-life scenarios, simulation games promote learning through physical activities and enable individuals to translate their knowledge into practical skills (Galloway, 2004). Visual representations of processes and metrics play a crucial role in helping players understand the consequences of their decisions and strategies in these games. By presenting data in a visually engaging manner, players can easily grasp the impact of their actions and make informed decisions to improve their performance. This enhances the learning experience and allows for a deeper understanding of Lean principles (Shannon et al., 2010).

SPAGHETTI DIAGRAM

A spaghetti diagram is a technique used to visualize the movement of an object in a system (Kanaganayagam et al., 2015). Due to the likeness of the results to cooked spaghetti, the tool was given the name spaghetti diagram.

Within the Lean manufacturing paradigm, spaghetti diagrams are commonly utilized as improvement tools (Gladysz et al., 2017). A spaghetti diagram can be used to identify movement durations, multiple movements and overlapping motions. Transportation and motion wastes are revealed using a spaghetti diagram, enabling the reduction of unnecessary labor, and modifications to organizational structure or workstation arrangements (Senderska et al., 2017).

These diagrams are a tried-and-true method for finding layouts that work better (Bicheno & Holweg, 2008). It is relatively simple to identify opportunities to decrease movement waste when the transportation routes are made clear. This visual transparency makes it possible to analyze each movement, revealing areas where motions can be improved. Staff members or workers are observed performing their duties, and the route they take is graphically traced onto a two-dimensional floor plan (Lean Consulting Group, 2016).

The spaghetti diagram is a valuable tool for enhancing our understanding of work processes, particularly when it comes to the distances travelled by production workers. Inefficient material staging arrangements resulting in waste from unnecessary and empty transportation can often be addressed through the rapid visualization of movement, even with modest technologies.

While traditionally hand-drawn, the development of software products is now facilitating the process of creating spaghetti diagrams. By capturing a worker's motions throughout the work cycle being studied and tracing them onto a two-dimensional plan, a spaghetti diagram can be created with greater accuracy and efficiency. Using software such as visTABLE® is a logical and practical approach to creating spaghetti diagrams and is certainly helpful during design of projects such as healthcare facilities where movements of healthcare workers should be minimized (Weber, 2022). While visTABLE® software is a logical tool for creating spaghetti diagrams, it currently cannot generate diagrams in real-time. To address this limitation, this research explores the effectiveness of a dynamic post-action spaghetti diagram incorporated into an online game in improving worker performance. One potential issue with using spaghetti diagrams is the possibility of altered behavior from workers who are aware of being observed. To address this concern, a dynamic spaghetti diagram can be constructed continuously and without the knowledge of workers being analyzed, providing a potential remedy to this drawback (Gladysz et al., 2017).

AWARENESS ENHANCEMENT

An expanding number of research studies support the use of visualization as a tool for problem solving and awareness enhancement. Visualization improves information comprehension by encouraging immediate linkage and perceived associations. In order to achieve this, information must be presented in a way that makes it easier for a user to process it and reduce the amount of mental adjustments needed (Livnat et al., 2005).

For example, in studies focused on raising energy awareness, visibility of energy consumption appears to play a crucial role. According to a survey by Hassan et al. (2009), increased visibility of energy use motivated users to reduce energy consumption. Additionally, a study conducted by Jachimowicz et al. (2018) showed that sharing energy use data with users resulted in energy savings between 0.81% and 2.55%. Sharing this kind of data with users appears to increase their awareness and alter the direction of their actions. When unbiased measurements make them more aware of their actions, users appear to better grasp what they are doing that jeopardizes a goal and what they need to change to reach that goal.

The use of visual management (VM) technologies has grown, and successful implementation instances have been recorded (Brandalise et al., 2022; Tezel, 2011). VM is a component of the Toyota Production System (TPS) and is frequently linked to lean construction (Koskela, 1992). Applications for visual management are designed to make information more easily accessible so that process participants can take appropriate action at the right time (Koskela, 2001; Liker et al., 1995). For example, the increasing ubiquity of BIM facilitates VM before actual construction. By analysing the frequency and intensity of a worker's actions, non-value-adding activities (waste) are easier to identify. Project managers, superintendents, and foremen can benefit from developing situational awareness, but it is arguably equally important for workers to develop this skill by offering them a before-and-after "snapshot" of their own movements (Ghimire et al., 2017; Reinbold et al., 2019).

RESEARCH GAP

The objective of this study was to examine whether exposing individuals to digitally generated spaghetti diagrams can enhance their personal awareness of value-adding and non-value-adding activities, and lead to a reduction in their own movements. However, the creation of accurate spaghetti diagrams is a skill that requires time and practice. Furthermore, existing diagrams are often static and fail to capture transportation dynamics (Gladysz et al., 2017). In response to this need, a real-time diagram-generating algorithm was incorporated into an online game developed for this research.

The following were the procedures and objectives of this research study:

Develop a real-time spaghetti diagram into an online game which can incorporate distance travelled; and

Collect feedback to determine whether or not the spaghetti diagram generated by the online game helps participants identify opportunities for enhanced productivity.

The research question was as follows: Will students and construction professionals enhance their performance (reduce motion and transportation) when exposed to visual spaghetti diagrams incorporated into an online game?

RESEARCH METHOD

The cross-platform game engine Unity® 3D by Unity Technologies was used in this research to develop a game to determine if a spaghetti diagram could heighten player awareness of opportunities to improve their productivity. Because AEC stakeholders perform a wide range of activities defined by their specific roles, the game was designed to engage participants in a universal activity that is widely relatable to actors across multiple fields and cultures—e.g. the act of making spaghetti (Arefazar & Rybkowski, 2022). The game was inspired by the authors' anecdotal observation that construction workers responded well to a video entitled "Toast Kaizen" (GBMP 2009); these workers argued the video was effective in helping them understand waste identification and elimination on-site because toast-making is a shared experience. The intent is that this simulation may offer a first exposure to participants to waste recognition with the expectation that the graphics could then be replaced with materials and activities related to a stakeholder's specific role, such as supply-chain management, material delivery and laydown areas, equipment placement, structural erection, bricklaying, roofing, etc.

The game was designed in such a way that it could be played using a laptop. The game was designed in 3D view and the view that appears in the game is the plan view. To stage the making of spaghetti, the game depicts a kitchen layout that includes kitchen appliances, utensils, and ingredients needed to make a full plate of spaghetti with meatballs. An avatar cook starts walking when the player clicks on a desired destination. When the cook is close to an object, the object will automatically light up, which signals that the cook can grab that object.

This game has a notable feature of tracking and recording the total distance the player's cook has walked. This information is displayed on the right side of the kitchen's layout after each scenario is completed. The game's objective is to deliver a cooked dish (spaghetti with meatballs) with the least possible distance traveled, and the order of activities is not crucial. Two versions of the simulation were available to players: the control version (Figure 1; orange background) did not provide access to a spaghetti diagram of the cook's movements, while the experimental version (Figure 2; green background) displayed a complete history of the cook's movements via a spaghetti diagram at the end of play. Both versions show players the kitchen, utensils, player's name, level played, travel distance, and elapsed time.

DATA COLLECTION

The research was approved by the Institutional Review Board by Texas A&M University and participants were emailed a consent form before play. The control group participants played the game without being shown a spaghetti diagram, while the experimental group was shown a spaghetti diagram of their path after each round. The experimental group participants' movements were tracked, and a spaghetti diagram was generated on the screen. During the first round, the kitchen layout was pre-set by the program and the layout was identical for each participant; however, during a subsequent round, participants were asked to make a decision about potentially modifying the layout of the kitchen by relocating a stove to one of three possible locations (A, B, or C) as shown in Figure 3.

After each round, the experimental group participants were asked to describe how they used the spaghetti diagram, if at all, to identify a strategy to improve their performance.

After completing the game, both groups were requested to provide plus/delta feedback which is a common tool in Lean philosophy to identify what is working well enough to be retained (plus) and what could be improved (delta). Their feedback was used to improve the game and fix potential deficiencies.

The null hypothesis (H0) and alternative hypothesis (H1) of this research were as follows:

H0: There is no significant difference in improved performance between the control group and the experimental group. Being shown a spaghetti diagram of the cook's path did not help the participants improve their performance.

H1: There is a significant difference in improved performance between the control group and the experimental group. Being shown a spaghetti diagram of the cook's path helped the participants improve their performance.

The researchers aimed to investigate the effectiveness of the spaghetti diagram in enhancing the participants' ability to identify opportunities to reduce motion. To achieve this goal, the study included two groups of participants: an experimental group of 30 individuals and a control group of 30 individuals. The researchers collected performance data from each participant in both groups and compared the results. To test the alternative hypothesis, the researchers employed an unpaired t-test as a statistical analysis method.

DATA ANALYSIS

Information related to the online game participants is depicted in Table 1. Students played the online game during in-person sessions. A live facilitator explained the rules and was available for the duration of the session to help participants with any questions they might have.

For the test session with online lean simulation experts called APLSO (Administering and Playing Lean Simulations Online), the facilitator explained the rules and instructions and randomly divided participants into two separate breakout rooms (i.e., control and experimental) using Zoom. Separate links to the game were sent to each group, and they were invited to play. Since learning to play the game effectively takes some practice, the researcher compared participants' performances between Levels (i.e. "rounds") 1 and 4. The difference between the average distances between Rounds 1 and 4 shows improved performance. The mean of the enhanced performance for the control group was -5.23 units. The negative value indicates that the travel distance was shortened (i.e., improved by 8.4%) in the latter round.

The experimental group played a version of the online game in which the spaghetti diagram was depicted at the end of play. The distance travelled and selected layout for each round was collected. According to Table 2, the difference of the average distances between rounds 1 and 4 shows improved performance. The mean of the enhanced travel distance performance for Group B (experimental) is -10.86 units. The negative mean suggests the cook's path in round 4 versus round 1 was shortened by 10.86 units (improved by 51.84%), which is greater than that found for Group A (control). A comparison of the averages of the improved performances between the two groups suggests that the participants who played the version with a spaghetti diagram showed greater improvement in terms of travel distance. Data collected from Group A (control) and Group B (experimental) are summarized in Table 2. The control group played a version of the online game in which participants were given access to their travel distances after each round; however, a spaghetti diagram was not made available to them.

Although the improvement in travel distance for participants using the spaghetti diagram was not statistically significant, data analysis revealed that the experimental group was more successful in identifying an optimized layout for the kitchen. Specifically, 70% of the experimental group participants chose layout C, compared to only 30% of the control group participants. This suggests that the spaghetti diagram was effective in helping participants understand that layout C, which involves placing the sink and stovetop closer together, would reduce wasted transportation and motion (as measured by travel distance).

Results of the paired t-test results are as follows:

The two-tailed P value equals 0.1261. This difference is not considered statistically significant. Therefore, the null hypothesis cannot be rejected and a spaghetti diagram of the cook's path did not help the participants improve their performance;

The mean of the Control Group minus the Experimental Group equals 5.63; and

A 95% confidence interval of this difference is from -1.633 to 12.96.

To further illustrate this point, Figures 4 and 5 depict examples of spaghetti diagrams that experimental group participants saw after playing each round. The spaghetti diagram in Figure 4 shows a total travel distance of 53.07 units for layout A, where the stove is located further from the sink. In contrast, the spaghetti diagram in Figure 5 shows a total travel distance of 42.89 units for layout C, where the stove is located close to the sink.

Interestingly, data analysis showed that layout C was the only layout where participants could minimize their travel movements. Moreover, the best performance among participants came from a participant in the experimental group. To determine the significance of this result, a Chi-Square test was performed, resulting in a chi-square statistic of 9.6 and a p-value of 0.001946. This indicates that there was a significant difference between the experimental and control groups in terms of choosing layout C, as shown in Table 3.

Figure 1: Spaghetti Kitchen Online Game (Control Version)

Figure 2: Spaghetti Kitchen Online Game (Experimental Version)

Figure 3: Stovetop Layout Options Given on Both Experimental and Control Versions.

Table 1: Online Game Participants and Dates

1	Students	37 graduate students taking COSC663 (Sustainable Construction) at Texas A&M University.	09/22/2022
		15 masters and PhD students from the Department of Construction Science at Texas A&M University	09/28/2022
2	Lean experts	8 Lean Experts from APLSO*	10/03/2022
		*Administering and Playing Lean Simulations Online (APLSO) is a voluntary, international online lean construction group that tests and gives feedback on novel online lean simulations.	

Table 2: Comparison of mean travel distances between control and experimental groups

	Group A (Control)	Group B (Experimental)
N	30	30
Mean	-5.2253	-10.8617
Standard Deviation	12.0122	15.8546
Standard Error of the Mean	2.1931	2.8946

The experimental group participants were asked to provide feedback on how they used the spaghetti diagram to identify strategies to improve their performance. The responses provided valuable insights into the benefits of using the spaghetti diagram, including:

Identifying and focusing on long travel distances;
Visualizing their movements through the spaghetti diagram;
Recognizing the importance of having utensils, stove, and sink located closer to each other to reduce unnecessary time and space requirements;
Optimizing the layout by placing the stove closer to the sink;
Organizing the retrieval of items in a logical order based on distance traveled;

Gaining a better understanding of their displacement and movements through the geometry of the spaghetti diagram and the repetitive lines, which showed where more attention was needed;

Designing a better path to improve their workflow; and

Identifying and eliminating wasteful movement.

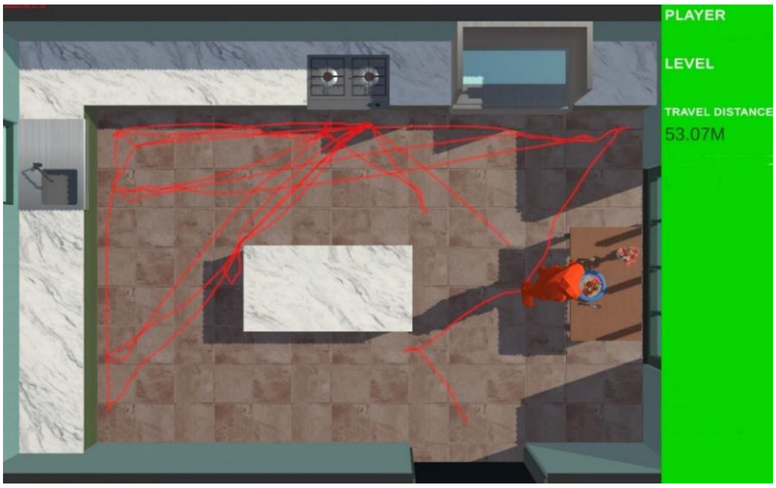

Figure 4: Example of spaghetti diagram in layout A.

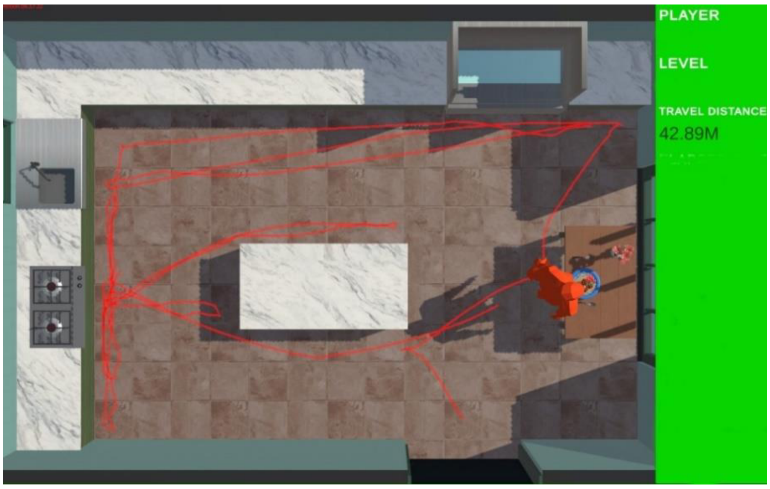

Figure 5: Example of spaghetti diagram in layout C.

Finally, feedback from participants of the online game was collected and examples of feedback included: *Plus*: Engaging graphics, fun to play, intuitive, useful; *Delta*: Add more options for rearrangement of appliances and create next stage of this game for construction.

Table 3: Number of times layout C was chosen by participants.

Type	Layout C	Other Layouts	Row total
Experimental Group	**21**	**9**	**30**
Control Group	**9**	**21**	**30**
Totals	**30**	**30**	**60**

These findings underscore the potential benefits of using spaghetti diagrams in optimizing workflow and reducing waste in a variety of contexts. Although further research is certainly needed to fully explore their impact, the study provides potential insights into their effectiveness in the context of layout optimization.

DISCUSSION

There are certainly limitations to this research. For example, different participant groups were combined due to time and resource limitations, and the sample sizes were relatively small. The researchers did not ask participant to share their background so there is no knowledge about which players may have more experience with Lean and waste identification than others. Another limitation of the research itself is that the game was primarily tested on university-level graduate students who plan to enter the construction industry. As such, the research represents a first-run study. Further research with on-site construction workers and project managers is needed to validate the simulation's effectiveness within the construction industry.

There are limitations with the currently designed game as well. For example, the designed online game cannot be played until the rules and instructions are explained to players. Instructions can certainly be shared through a pre-recorded video, for example, but there are benefits to having a live facilitator assist participants who may need additional guidance regarding moving and interacting with the objects. Playing should be followed up with discussions about potential applications to actual construction scenarios as the intent of using a commonly shared activity such as making spaghetti is to introduce participants to a fundamental lean concept that then can be applied to a task to which many participants can relate. For example, by using a software program, steel girders can digitally replace packages of spaghetti and cranes can easily be swapped with stove tops.

The ultimate goal of this work is to help users heighten their awareness of ways to improve workflows using the online game as a preliminary training tool to expose participants to their own movements. The intent is to help them self-identify wasted movement and therefore opportunities for productivity improvement when performing their own work. Because they are automated and internet-accessible, both the video and online simulation game offer the possibility of expanded geographic reach to potentially exceed what physical, in-seat simulations can do. This can offer a substantial benefit to multinational companies seeking to simultaneously train personnel in different parts of the globe.

CONCLUSION

Results from this research suggest that spaghetti diagrams, and other alternative ways to map construction processes, may be effective in increasing awareness of waste reduction and improving performance among those trained in the construction industry. There are opportunities for future research, including investigations into the applications of this simulation to actual construction scenarios. This could involve tracking and recording movements of workers or equipment and projecting them onto the ground in the shape of a spaghetti diagram for visual observation.

By adapting the online simulation game to depict construction activities on an actual project, with locations for material delivery, logistics, and laydown areas, there is potential to further enhance the game's effectiveness. Additionally, designing and testing the game in a three-dimensional (perspectival) view instead of a two dimensional (plan) view could provide valuable insights into its intuitiveness and effectiveness for those practicing in the construction industry. Overall, these findings offer exciting possibilities for future research and innovation in this field.

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EXPLORATION OF EDUCATIONAL BACKGROUNDS, PERSONALITY TRAITS, AND GENDER ON TENDENCIES TO COLLABORATE AMONG OWNERS, ARCHITECTS, ENGINEERS, AND CONTRACTORS

Vishnu Ramanath[1] and Zofia K. Rybkowski[2]

ABSTRACT

The construction industry is challenged by a lack of collaboration and trust, leading to an adversarial relationship among project stakeholders. With the introduction of Lean-Integrated Project Delivery (IPD) processes, collaboration has become a key strategy for increasing productivity. This research leveraged game theory and the Maroon-White simulation to explore whether there is any correlation between the educational background of owners, architects, engineers, and contractors and their tendencies to collaborate. It also explored whether there is a correlation between tendencies to collaborate based on various personality types as measured by Jung/Isabel Briggs Myers typology. Although results from this research are preliminary, university students studying to enter the OAEC stakeholder practices (Owner Architecture Engineering and Construction) showed similar rates of tendencies to collaborate. Correlation with personality types was inconclusive. However, multiple rounds of play often revealed long-term negative impacts when one team betrayed a collaborative agreement for its personal benefit. Also, although teams with females did not significantly modify the numerical results, facilitators noticed that women often openly voiced that a collaborative strategy would gain the most points, yet their suggestions tended to be dismissed by teammates. Further research is needed in this area.

KEYWORDS

Lean Construction, Maroon-White Game, simulation, integrated project delivery, IPD contract, collaboration, trust, betrayal, personality traits, gender.

INTRODUCTION

The construction industry is confronted by challenges such as a paucity of collaboration and trust, ineffective communications, and a lack of systems thinking. These attitudes are arguably partly responsible for adversarial relationships between Owner, Architecture, Engineering, and Construction (OAEC) [3] stakeholders (Elmarsafi 2008). Collaborative friction can lead to project delays, difficulty in resolving claims, cost overruns, litigation, and a win-lose climate that affects

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[3] The acronym OAEC is used here instead of the more typical AECO to refer to Owner Architect Engineer and Contractor stakeholders. The (re)ordering is intentional to acknowledge the primary focus of the team in Lean-IPD is to align with the Owner's needs.

all the project stakeholders. It is therefore worthwhile to explore tendencies toward collaboration or non-collaboration among students who are being educated to enter OAEC-related practices.

Research shows that with the evolution of construction projects from Design-Bid-Build[4] to the Design-Build[5] and Integrated-Project-Delivery[6] (IPD) methods, the need for collaboration is high. Shelbourn et al. (2007) argues that with advancing methods, it is time for the construction industry to embrace new ways to improve productivity, mitigate litigations, and to deliver at its best the demands of the Owner. Also, the construction industry's success depends on the collective efforts of players from different companies and backgrounds. To achieve this, collaboration and trust among key players in the industry are critical.

Research suggests that for the implementation of Lean-IPD, collaboration plays an important role (Smith 2013). With lean manufacturing principles giving rise to lean construction, IPD processes have helped to improve collaboration levels among different key players (Mesa et al. 2019). Yet even with the implementation of IPD, lack of trust and collaboration among stakeholders still exists. One possible reason for deficits in collaboration is the uniqueness of each construction project; repeating partnerships do not happen often. Also, natural competitive tendencies can often spur on sub-optimization and subsequent long-term losses (Smith and Rybkowski 2013).

The objective of this research was to investigate the potential influence of the educational background of owners, architects, engineers, and contractors on tendencies to collaborate in the construction industry. Also, based on the assumption that extroverts may tend to collaborate more than introverts, the research attempted to determine whether this is true in the case of OAEC disciplines. Finally, the research serendipitously explored whether, when in competitive teams, women tend to collaborate more than men.

SIGNIFICANCE OF THE STUDY

Collaboration plays an important role in the success or failure of Lean-IPD. An understanding of cultural and educational tendencies towards collaboration or non-collaboration of stakeholders offers a glimpse into factors that might facilitate or impede collaboration. For example, by understanding if there are disciplines that have lower tendencies to collaborate, a college curriculum can be structured to address the importance of collaboration. Optimization of the whole over the parts is one of the key tenets of lean, and stakeholder understanding of it facilitates implementation of IPD.

THE NEED FOR INTER ORGANIZATIONAL COLLABORATION

Collaboration has been defined as the process of shared decision-making among independent parties, involving joint ownership of decisions and collective responsibility for outcomes (Boyle and Kochinda 2004). Collaboration includes supporting sustained teamwork by creating a culture that values personal integrity, giving power and respect to each person's voice, integrating individual differences, resolving competing interests and safeguarding the essential contribution each must make to achieve optimal outcomes (Sterchi 2007). To become successful at a job it is necessary to coordinate with others (Johnson and Johnson 2004). Collaboration can be the key to overcoming work-related obstacles (Vygotsky 1978).

Basic essential characteristics of a group setting should include the following: cooperation, conversation, teamwork, confidence and coherence (Greenlee and Karanxha 2010). Constructive conversation tends to bond team members together. Sarker et al. (2011) concluded that better interactions lead to higher levels of achievement.

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[4] Design and construction are separate contracts; lowest construction cost is the criteria for final selection (Kenig 2011)
[5] Design and construction contracts are combined (Kenig 2011)
[6] Key parties are involved from the inception of the project and use a multi-party contract (Kenig 2011)

Inter-organizational collaboration has been shown to create a strategic advantage in most industries. According to Schifrin (2001), strategic alliances are a common business strategy in the US with 10,000 partnerships being created each year. In an industry such as construction, the conditions for the practice of inter-organizational collaboration are ripe. Opportunism by team players is readily available in most construction projects and generally comes at the expense of the other players or the project as a whole (John 1984). Research has also identified trust as one of the most effective ways to prevent opportunism (Walker 2003). When group members are familiar with one another, it can lead to an improved team environment, which shows tendencies to collaborate (Janssen et al. 2009; Stark and Bierly 2009). Inter-organizational collaboration has been studied across industries and has been shown to increase organizational capabilities and value generation through exchange of resources—thus contributing to an organization's competitive advantage (McEvily et al. 2003).

INTEGRATED PROJECT DELIVERY (IPD)-COLLABORATION

Integrated Project Delivery (IPD) is defined as a "project delivery approach that integrates people, systems, business structure and practices into a process that collaboratively harness the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste and maximize efficiency through all phases of design, fabrication, and construction" (AIA 2007). IPD, in contrast to the traditional method of delivery, integrates all key players from the project's inception. It leverages early contributions and expertise through utilization of new technologies, allowing all team members to add value and to realize their potential for contributing to the project. IPD seeks to improve project outcomes through a collaborative approach of aligning the incentives and goals of the project team through shared risk and reward, early involvement of all parties, and a multiparty agreement (Kent and Becerik-Gerber 2010).

Collaborative working is considered by many to be essential if design and construction teams are to consider the whole lifecycle of the construction process (Shelbourn et al. 2007). Inherent within this agenda of new ways of working is a move toward collaborative working and its associated fields: concurrent engineering and lean production (Anumba et al., 2004). Collaboration is essential if design and construction teams are to address the entire lifecycle of the construction product and take account of not only primary functionality but also productivity, buildability, serviceability, and even recyclability (Kusiak and Wang, 1993). Cooperative relationships among the supply chain actors (referred to as partnering) are an important element of lean construction (Naim and Barlow, 2003; Green and May, 2005; Jorgensen and Emmitt, 2008), facilitating the integration of different actors' competences and efforts toward joint problem-solving. At the core of IPD are collaborative, integrated and productive teams composed of key project participants (AIA 2007, Mesa et al. 2019). Guided by principles of trust, transparent processes, and effective collaboration, the IPD teams build upon early contributions of an individual's expertise.

New technologies when utilized in conjunction with collaborative processes are demonstrating substantial increases in productivity and decreases in requests for information, field conflicts, and other forms of waste (AIA 2007). AIA claims Integrated Project Delivery is built on collaboration, which in turn is built on trust. With better collaboration, the key players focus more on the success of the project rather than on individual goals. Without collaboration, IPD will falter, and participants will remain in the adverse and antagonistic relationships that plague the construction industry (AIA 2007). Kulkarni et al. (2012) discovered that collaborative project delivery systems produce more reliable cost outcomes for public owners. One of the factors that can undermine implementation of IPD is fear of loss of individual interest. Huxom (1993) claims that the key disadvantages of collaboration are loss of control, flexibility, and glory. Despite these disadvantages, however, the benefits of collaboration override the disadvantages (Huxom 1993).

EDUCATIONAL INFLUENCE ON TENDENCY TO COLLABORATE

Collaboration has been studied substantially in a variety of fields. Borrego (2006) claims that engineers tend to view collaboration as an isolated division of labor and the views on collaborative relationships vary markedly between technical and social science fields. Also, Borrego et al. (2008) observed that the way an individual understands and appreciates the nature of knowledge affects the way he or she collaborates with colleagues in different academic disciplines. According to Lin and Darnall (2015), some organizations find it difficult to configure alliances for mutual benefit, resulting in the failure of half of strategic alliances.

With the advent of IPD, inter-organizational collaboration plays an important role. AIA claims that without collaboration IPD fails. In recent decades, collaborative working has focused on the delivery of technological solutions (Faniran et al. 2001; Karasu et al. 2022). There is a need for research on the human-related factors influencing the level of collaboration among the project stakeholders.

Borrego (2008) observed that the way an individual appreciates the nature of knowledge affects the way he or she collaborates with colleagues in different academic disciplines. Much of the research on the topic of influence of educational background on the level of collaboration has been conducted in the fields of health care, engineering, and social science. For example, Stacy (2007) claims that nurses have a better collaborative approach than physicians.

WOMEN AND TENDENCY TO COLLABORATE

According to research literature, women tend to be less competitive than men. Gneezy et al. (2003) found that women were less effective than men in competitive environments, despite the fact that their performance was similar to that of men in a non-competitive environment. Niederle and Vesterlund (2007) concluded that women tend to shy away from competition. In terms of group processes, Woolley et al. (2010), concluded that group collaboration is greatly improved by the presence of women in a group. In a study of group performances, Fenwick and Neal (2001) found that, on a management simulation task, groups with a greater number of women performed better than homogeneous groups.

In a meta-analysis comparing men and women in terms of task and interpersonal styles, Eagly and Johnson (1990) found that women were significantly more interpersonally oriented than men. The styles of males tend to be more autocratic than those of females (i.e., giving orders), whereas the styles of females tend to be more democratic than those of males (i.e. focus is on participation). In addition, when comparing all-female versus all-male groups, all-female groups demonstrate more egalitarian behaviors, such as equal amounts of communication among group members and shared leadership (Berdahl and Anderson 2005). While these findings may be undergirded by physiological and hormonal differences between males and females, results may also vary according to context and cultural practices.

GAME THEORY: PRISONER'S DILEMMA AND THE MAROON-WHITE GAME

The Prisoner's Dilemma has been defined as a paradox in decision analysis in which two individuals acting in their own best interest pursue a course of action that does not result in the ideal outcome. The typical prisoner's dilemma is set up in such a way that both parties choose to protect themselves at the expense of the other participant. As a result of following a purely logical thought process to help oneself, both participants find themselves in a worse state than if they had cooperated with each other in the decision-making process. The exercise explores the conflict between social incentives to compete versus those encouraging cooperation (Holt and Capra 2000). Research shows that when given the option to cooperate with another party or look out for one's own best interests, barring additional incentives, the selection of a cooperative move is unlikely (Axelrod 1981; James Jr. 2002; Smale 1980).

The Maroon-White Game is an example of prisoner's dilemma. The Maroon-White Game is a three-group non-zero-sum game. A non-zero-sum game describes a situation where one team scoring points does not necessarily mean that fewer points are available for the other teams (Von Neumann and Morgenstern 2007). This type of game is commonly used in situations where cooperation between teams is a possibility.

This study used the simulation, the Maroon-White Game (Smith and Rybkowski 2013), to explore whether the educational backgrounds of four different stakeholders (owners, architects, engineers and contractors) influence their tendencies toward collaboration. The Maroon-White Game helps reveal whether individualism is favored over collectivism or vice versa in an organization and in the industry in general. This research also explored whether women have a higher tendency to collaborate when compared to men and whether specific personality types as defined by the by Jung/Isabel Briggs Myers Typology test are more or less likely to collaborate.

RESEARCH METHODOLOGY

INTRODUCTION

This research asked the following question: Is there a correlation between educational background and tendency to collaborate (TTC), specifically among those preparing to enter OAEC practices following graduation? Also: Does personality type, defined by the Jung/Isabel Briggs Myers Type Indicator, make a difference? Does gender? To address these research questions, researchers invited fourth year undergraduate students at Texas A&M University to participate in the Maroon-White Game (Smith and Rybkowski 2013).

DATA COLLECTION

Courses at Texas A&M University in the four disciplines of Business, Architecture, Engineers, and Construction Science representing the Owners, Architects, Engineers, and Contractors in the construction industry were selected for participation.

A recruitment email was sent to instructors of courses in these disciplines asking their permission to administer the game in one of their classes. Participants were asked to sign off on an informed consent form, required by the Institutional Review Board (IRB of Texas A&M University). The game was administered to two (2) senior-level business classes, one (1) graduate-level business class, three (3) senior-level architecture classes, two (2) senior-level construction science classes, and one (1) senior-level civil engineering class. Also, the game was played with members of one (1) construction company during a separate facilitation.

RESEARCH TOOL: THE MAROON- WHITE GAME

Simulation games are commonly used for research and teaching in the field of Lean-IPD (Bhatnagar et al. 2022). The Maroon-White game was used to address the stated research questions and played according to instructions in Smith and Rybkowski (2013). The Maroon-White Game was derived from the Red-Black Game outlined on the College of St. Benedict website (CSB-SJU n. d.) and was facilitated as follows: The facilitator divides participants into three teams: A, B, and C, and writes a score chart (Figure 1) on a chalkboard, flip chart, white board, etc. or projects the chart on a wall for everyone to see. Each team is given two cards written with "M" (maroon) and the other with "W" (white). Teams are instructed to discuss their decision to simultaneously hold high either the M or W card when instructed to do so. The facilitator repeats only one phase: "The object of the game is to gain the maximum number of points." Participants successively play seven (7) rounds and after each round the score is recorded. Teams are permitted to send an ambassador to negotiate with the other teams' representatives starting from Round 3. If participants ask whether the maximum number of points is for the total group or individual teams, the facilitator simply states "both," and repeats: "The object of the game is to gain the maximum number of points."

If all teams declare "white" by the third round, the facilitator can invite each team to send an ambassador for a few minutes outside the room to negotiate on their behalf. The game is finished after seven rounds of play.

	A	B	C
MMM	50	50	50
WMM	100	0	0
WWM	0	0	0
WWW	0	0	0

Figure 1: Maroon-White Game Scoring Chart

Discussion following play included asking the following questions: What is the best way to maximize your points? What did you learn from this game? How did a betrayal (if any) affect your decision as a team? Once the trust is lost by selecting white, what effect did it have on you as a participant? How can this game be applied to construction? What factors affect one's ability to maximize points?

For this study, the number of female participants and personality types was collected. The researchers acknowledge that the Jung/Isabel Briggs Myers Typology Test is just one of several recognized personality tests; however, as it is widely known and used, the test was selected and virtually administered to participants before the game as one way to determine the personality type of the participants. The test defines 16 personality types made from the following combinations: E (Extraverted) vs. I (Introverted); N (Intuitive) vs. S (Sensing); F (Feeling) vs. T (Thinking); J (Judging) vs. P (Perceiving) (Human Metrics n. d.).

DATA COLLECTION & ANALYSIS

Data collected included:

- TTC (Tendency to Collaborate) = (Number of Maroon Responses ÷ Total Number of Responses) *100
- The percentage of women in each team
- The percentage of extroverts per team.

The left and right tallies in Figure 2 represent the worst and most-commonly observed scenarios, respectively. The middle tally shows the results if the teams pursued a collaborative approach. If the teams collaborate in each round, the maximum points that each team could gain is 350–and the total points would be 1050. A fully collaborative approach maximizes both the individual team points and total points. Teams play seven (7) rounds to mimic a potential real-world scenario where individuals elect to trust or not trust other individuals and teams, based on prior experience with those actors.

Table 1 lists the average TTC observed for Business Seniors, Business Graduates, Construction Science Seniors, Civil Engineering Seniors, Architecture Seniors, and the construction company. Figure 3 compares their TTC, showing similar rates of TTC per discipline. TTC is the lowest for the construction company when compared to the average TTC across Business Seniors, Business Graduates, Civil Engineering Seniors, Construction Science Seniors, and Architecture Seniors at Texas A&M University. Teams A and B consistently declared white, while team C frequently declared maroon. The low TTC among many members of the construction company may be attributed to the fact that teams A and B worked daily with subcontractors on low bid projects and so were unwilling to extend trust (according to teams A and B) while team C was composed entirely of estimators who stated they trusted one another.

The average TTC for all the academic disciplines was found to be 36.34% and the TTC for the construction company was lower than the than the average TTC among disciplines by 12.54%.

Comparing only the disciplines across Texas A&M University, it can be observed from Figure 3 that the architecture senior students had the highest TTC with 39.15%. The business graduates and the civil engineering seniors had the second highest TTC with 38.09%. Construction Science seniors had the third highest TTC with 37.80%. The business seniors had the lowest TTC when compared to all the other disciplines with TTC of 28.56%, however this may simply reflect natural variation. Ultimately, there was no evidence that the level of collaboration is influenced by educational background. To verify whether gender plays any role in levels of collaboration, the percentage of females per team was calculated and their TTC was plotted in scatter plot. Figure 4 shows the scatter plot of percentage of women per team and their TTC.

Worst Case Scenario

Rnd		A	B	C	
1	WWW	0	0	0	0
2	WWW	0	0	0	0
3	WWW	0	0	0	0
4	WWW	0	0	0	0
5	WWW	0	0	0	0
6	WWW	0	0	0	0
7	WWW	0	0	0	0
		0	0	0	0

Best Case Scenario

Rnd		A	B	C	
1	MMM	50	50	50	150
2	MMM	50	50	50	150
3	MMM	50	50	50	150
4	MMM	50	50	50	150
5	MMM	50	50	50	150
6	MMM	50	50	50	150
7	MMM	50	50	50	150
		350	350	350	1050

Most Common Scenario

Rnd		A	B	C	
1	WWW	0	0	0	0
2	WWW	0	0	0	0
3	MMM	50	50	50	150
4	WMM	100	0	0	100
5	WWM	0	0	0	0
6	WWW	0	0	0	0
7	WWW	0	0	0	0
		150	50	50	250

TTC (left to right): (0/21) = 0% ; (21/21)*100 = 100% ; (6/21) = 28.5%

Figure 2: Possible Combinations and Commonly Observed Results.

Table 1: Disciplines and Their Average TTC (Tendency to Collaborate)

Group tested	No. of participants	TTC (mean %)
Business Seniors	44	28.57
Architecture Seniors	43	39.15
Construction Science Seniors	35	37.80
Business Graduates	16	38.09
Civil Engineering Seniors	14	38.09
Construction Company	13	23.80
	165	34.25

Note: The full set of results data for this research is available at Ramanath (2014). The mean TTC of student teams was 36.34%.

Because the percentage of female participants in each team was small (24% on average), it cannot be concluded that there is a difference in the level of collaboration based on the gender (Figure 4). However, if the women on the teams (the minority) had an intention to collaborate there is a possibility that the men on the teams (the majority) who did not wish to collaborate dominated. For example, it was observed that, in several instances, the individuals who suggested to collaborate while playing this game were females who were silenced, and their recommendation dismissed by teammates. We do not know whether the results would have been different had the teams been composed primarily of women. This needs to be further tested with larger sample sizes.

To verify whether the personality types play a role in the tendency to collaborate, the percentage of each personality type in each team was calculated and its TTC graphed in a scatter plot. From Figure 5 it can be seen that there is no significant statistical evidence to show that extroverts, intuits, feelers, and the judgers have a better tendency to collaborate when compared to the introverts, sensors, thinkers and feelers respectively. However, it cannot be concluded that personality types do not influence the tendency to collaborate. To validate the results, more research needs to be done on the personality traits and their influence on tendency to collaborate.

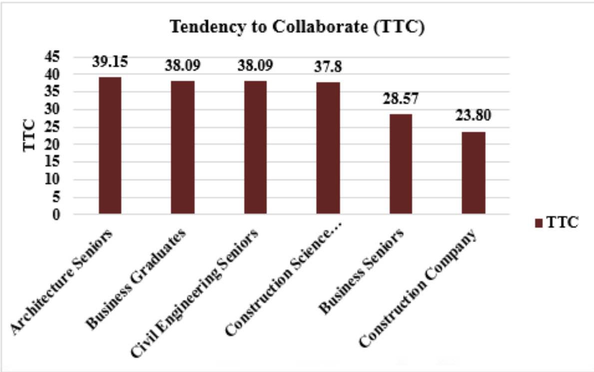

Figure 3: Disciplines and Their Average TTC

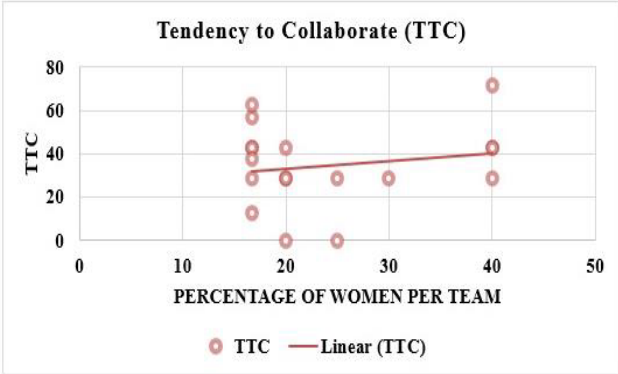

Figure 4: Percentage of Women per Team and Their TTC-Scatter Plot

DISCUSSION

A majority of the OAEC students from Texas A&M University appeared driven by competition during the initial rounds of the Maroon-White Game. It was observed they had an attitude of individualism over collectivism. It appears that natural competitive tendencies can often result in sub-optimization and long-term losses (Smith and Rybkowski 2013) and that these tendencies held true for the games administered. Researchers observed that an inability to collaborate with other teams prevented potential gains both in the short- and long-term. There seems to be a natural proclivity not to trust other teams in a competitive environment. The majority of participants chose "white" as their first choice during the game as they did not initially perceive the numerical benefit of collaborative thinking. Also, it was seen that the tendency to betray was often highest after gaining trust from other teams that agreed to declare "maroon." In other words, one team would often betray the other two teams even after all agreed that they would choose maroon. Subsequent to a betrayal, the other two teams would refuse to place themselves in a situation where they might be taken advantage of again, ultimately reaching the point where all three teams selected "white" during each round; teams even openly stated their intentions of doing so indefinitely. In fact, in only one (1) out of the ten (10) trials were teams able to regain collaboration following a betrayal. Because it is played in multiple rounds, the Maroon-White Game can be used to demonstrate to participants how natural tendencies to sub-optimize can substantially and negatively impact long-term gains, trust, and collaboration.

An unexpected outcome from observations of the M/W Game is that a formal, legally enforceable IPD contract is potentially preferable as it can help protect those who act with the expectation that others are trustworthy. This is because the "most common scenario" shown in Figure 2 illustrates how frequently one team chose to renege their verbal commitment to collaborate; most teams refused to collaborate during subsequent rounds following a betrayal. This recommendation differs from the partnering agreements popular in the 1990s where signed partnership agreements represented intentions to collaborate but did not hold legal standing.

Although this game is not an exact simulation of project delivery processes, it can arguably mimic the typical mindset of industry stakeholders and depict their typical decision-making processes. As discussed earlier, once the game was completed and outcomes discussed, a majority of participants agreed that collaborating maximized points and that they were sub-optimizing by not collaborating. The initial lack of trust and the betrayal impacted future decisions. This outcome demonstrated the need to develop sustained long-term relationships in the industry, and an integrous reputation to undergird trust. This game demonstrates that the tendency to sub-optimize can damage the development of a long-term sustained relationship. Interestingly, when Gandhi (2014) used the M-W game to test TTC of architecture students, he found a slight drop in students between their first and fourth year, suggesting a possible erosion of trust over time. Similarly, in this study, those working for a general contractor showed a lower TTC than the university students; this may also represent a further decline of trust once stakeholders enter the industry. Also, with respect to the general contractor, two of the three teams that worked daily with subcontractors[7] in the field argued their work "taught them never to trust" which helped explain, they said, why they insisted on declaring "white" and never "maroon" throughout the game. The only team that showed any tendency to collaborate explained that they were all estimators for the same company, so were accustomed to extending a level of trust between themselves.

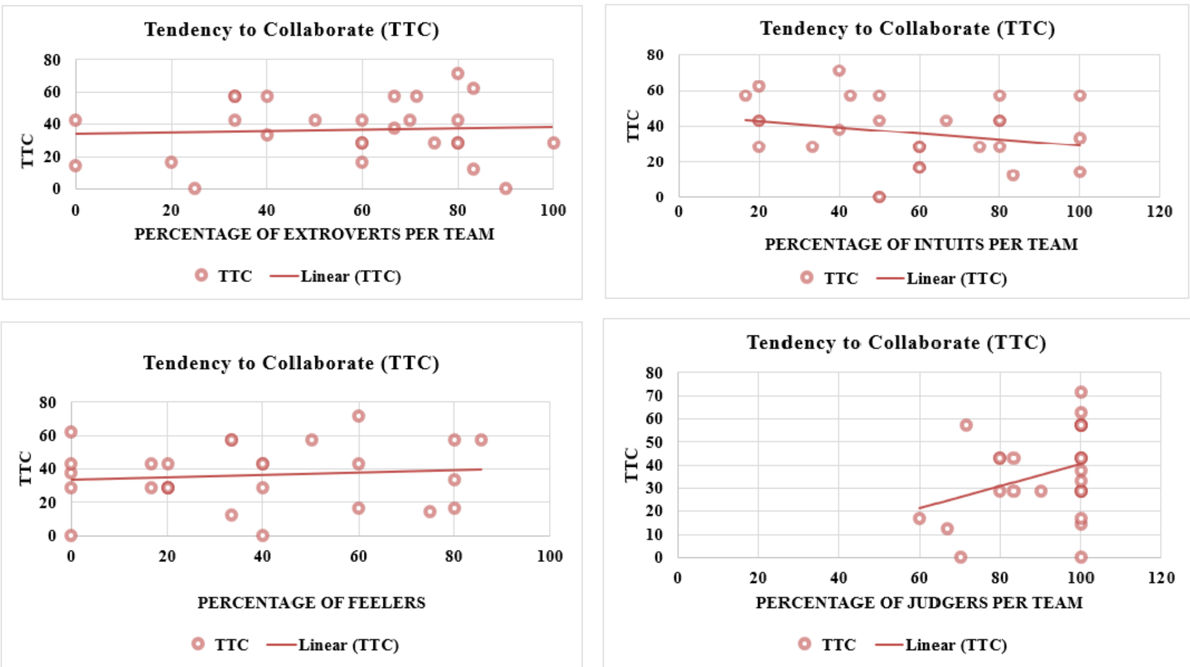

Figure 5: Percentage of Extroverts, Intuits, Feelers, & Judgers per Team and Their TTC

One important lesson from the game is that collaboration is important for sustaining long-term relationships. During the post-game discussion, participants stated the following factors that affected their tendency to collaborate: Absence of trust; lack of proper incentives; past experience; fear of betrayal; personality types; competitiveness; not seeing the long-term benefit; cultural differences; not knowing people enough or lack of a previous relationship; and favoring capitalism.

Recommended countermeasures to improve collaboration in the construction industry included: Change of mindset by playing games such as M-W; collaborative project delivery methods such as IPD; early negotiations; early and constant communication among stakeholders; setting expectations among stakeholders and informing them; mutual respect; and sustainment of long-term relationships to develop trust.

There were of course limitations with this exploratory research. For example, personality profiles of teams were collected in aggregate and individual correlations were not tracked per se. Also, prior collaborative work experience of participants was not tracked. Finally, larger sample sizes are needed to achieve statistical significance.

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[7] The term "subcontractor" is used here rather than the preferred term "trade partner" because the former was the term used by the general contracting company that did not practice Lean-IPD at the time of play.

CONCLUSION

This research investigated the tendency to collaborate among different disciplines. The average TTC's for business seniors, architecture seniors, engineering seniors and the construction science seniors were found to be 28.57%, 39.15%, 38.09%, and 37.80% respectively. The average TTC of business graduate students was found to be 38.09%. The architecture seniors had a higher TTC compared to all other disciplines. However, overall differences in TTC were not highly significant.

Of special interest is the observation that an actual construction company had a lower TTC than the average of student groups tested. It would be helpful to study this phenomenon further to determine whether the outcome is generalizable to include other general contractors and if so, why this might be so. Finally, how might contractors perform that are already accustomed to Lean?

This research also provided a platform to verify whether gender influences tendencies to collaborate. Based on numerical results, it appeared that gender did not appear to have an influence on tendency to collaborate. However, these final numerical outcomes were at odds with facilitators' observations that several females attempted to recommend collaboration during play, but their recommendations were often dismissed or ignored. Further research in this area is worth pursuing.

This research also explored whether personality types play a role in the tendency to collaborate. By comparing the percentage of extroverts, intuits, feelers, and judgers in each team to their TTC, there was no statistical evidence to conclude that personality types have an influence in the tendency to collaborate. However, further research is required to statistically validate the results.

Finally, the research revealed the corrosive effect of a single betrayal on the decision of the other teams to continue to collaborate. Recovering to a state of collaboration and trust seemed extremely difficult as only in one case out of ten were the teams able to collaborate fully once trust had been betrayed.

Opportunities for additional future research include exploring how the M/W game might be used to identify readiness of teams for IPD. It would be worth investigating if the game can help heighten awareness among project team members about the benefits of developing a more collaborative mindset before embarking together on an actual Lean-IPD project. It would also be valuable to systematically test to see if there may be generalizable differences in the tendency to collaborate between females versus males.

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OVERCOMING THE BARRIERS TOWARD WIDESPREAD ADOPTION OF PREFABRICATION: AN APPROACH INVOLVING EMERGING TECHNOLOGIES

Tran Duong Nguyen[1] and Pardis Pishdad-Bozorgi[2]

ABSTRACT

Today, prefabricated construction is rapidly expanding due to the development of factory-prefabricated components, fast construction site assembly, and sustainability. Despite the advantages, there are several problems, such as a lack of process standardization, poor communication and coordination, a lack of variety and transportation logistics, and a lack of trust and collaboration among stakeholders. Fortunately, the successful evolution of emerging technologies has facilitated growth in the building sector. By implementing literature reviews, this research aims to understand better the issues disrupting the widespread adoption of prefabricated construction and integrate innovative solutions and approaches to these issues. We will discuss prefabricated construction and its applications within the building sector by (1) comparing it to conventional construction method; (2) investigating the advantages and barriers toward widespread adoption of prefabricated construction; (3) developing an approach for applying advanced technologies in prefabrication, and (4) applying an approach to demonstrate how prefabrication overcomes conventional building issues. Our research suggests that an integrated approach combining advanced technologies during the prefabrication process will help solve the most significant problems that construction projects face, such as productivity, quality, safety, and sustainability. Additionally, the integration will provide a promising strategy to transform the construction industry from traditional to industrial.

KEYWORDS

Prefabrication, modular construction, off-site construction, Building Information Modeling, Blockchain.

INTRODUCTION

Modular or prefabricated construction is one of the advancing breakthroughs in the construction industry (NIST, 2015). However, the outcome could be more encouraging due to a lack of standardization, poor communication, a lack of collaboration among stakeholders, and the complexity of transportation logistics (Z. Zhang et al., 2022). One of the main reasons that holds back the advancement and widespread application of modular construction is the need for more standardization (Razkenari et al., 2020). However, most modern buildings attempt a complex and innovative design. These designs need further preparation and customization (Eastman et al., 2011). Due to their lack of industry experience, most modular construction companies need

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assistance learning what is required on-site and how to proceed throughout the manufacturing phase. Moreover, there are several contracts because of the complexity and the many stakeholders involved in prefabrication (Razkenari et al., 2020). Also, their complexity has created confusion over time. The builders and suppliers keep facing their challenges and creating coordination and trust is a new challenge.

An answer to the need for coordination and trust among stakeholders in traditional construction practices has been the Integrated project delivery (IDP) method, along with a single Smart contract between various stakeholders. The same approach can be applied to solve a distinct set of problems in the modular construction approach since the foundation of these problems still needs coordination and trust among stakeholders. Technology such as BIM is commonly used to design projects. However, one critical approach is integrating the supplier and design teams right from the start so the feasibility of building the prefabricated blocks can be quickly done. The complexity of numerous contracts has limited each stakeholder's capacity and left no space for transparency. A single contract signed by all suppliers and builders prior to the start of the project is one solution.

Among construction technologies, BIM and Blockchain stand out as reliable and complete methods in construction because it is a potential instrument that helps stakeholders understand the advantages of prefabricated construction, allowing them to have better control. In conducting this review, this research attempts to answer the following key questions:
RQ1: What is the current state of prefabricated construction in research-related fields?
RQ2: What are the advantages and barriers of prefabricated construction compared to traditional building methods in terms of advanced technologies?
RQ3: What are the technological advancements or solutions in prefabricated construction from a research perspective?
RS4: How might emerging technologies promote prefabricated construction from a research standpoint?

The successful approach and widespread adoption of technology in prefabricated construction are the most promising strategies for transforming the construction mode from traditional to industrial. The purpose of this research is to examine the current barriers that are holding the prefabricated construction approach back and to bring solutions to those challenges using innovative technologies such as BIM and Blockchain. The authors hypothesize that advanced technologies assist in problem resolution in prefabricated construction.

METHODOLOGY

The authors conducted a literature review to find relevant data on the uses of emerging technologies as a solution to the barriers toward the widespread adoption of prefabrication. This study's methodology provides a set of data analyses to present the qualitative approach through concepts, experiences, and insight into scholarly publications. Initially, data was gathered from a variety of sources. The original search keywords are prefabricated construction, modular construction, off-site construction, emerging technology, Building Information Modeling, BIM, Blockchain, etc. The initial literature review identified research gaps and emerging trends in the construction industry's relevant modular or prefabrication topics. This step helped the researchers become familiar with the current state of knowledge and the constraints of a particular topic.

Additionally, the literature review attempted to answer the research questions raised below about applying technologies in prefabrication. The study provided basic knowledge on the uses of emerging technologies to solve the challenges in the prefabricated construction method and developed an approach for the data analysis. The research approach was used as a filter in the decision support framework, which will assist researchers in choosing technology for review. Lastly, the research applied the integrated approach for the applications of advanced technologies jointly to the prefabrication methods as a solution to the challenges that are consequences of the traditional construction methods, including BIM and Blockchain. The study delivered a research concept schema or a roadmap for academic researchers to analyze and discuss technologies using the suggested approach.

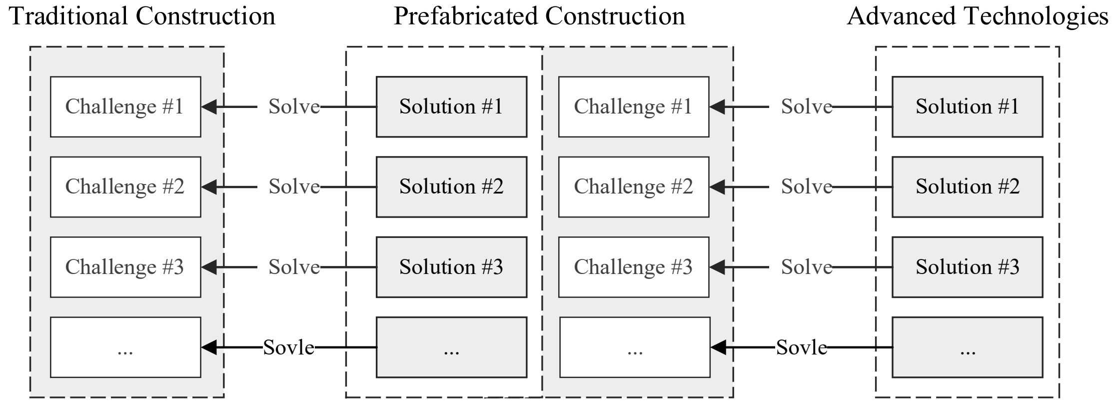

Figure 1: Proposed research conceptual schema

RESEARCH BACKGROUND

Several problems occur in the traditional construction method, one of them being sustainability, as 2.2 billion tons of construction waste are generated globally, of which 600 million are in the USA (*BigRentz*, 2021). Nearly 30% of all material delivered to the site ends up in the landfill. Construction costs rise, delays occur, and 98% of all construction projects incur cost overruns or delays (Tafesse et al., 2022). Time delays, productivity, and weather account for 60% of cost overruns (*Weatherbuild*, 2018). Safety is one factor that needs to be thoroughly enhanced regularly on the construction site, and it does not depend on physical health but on mental health. Noise pollution is abundant; 51% of all construction workers have experienced dangerous noise exposure, and approximately 14% of laborers have a hearing impairment (NIOSH, CDC, 2021). Construction methods and techniques also change with the seasons, so construction relies on clear weather; therefore, workers' livelihoods depend on weather conditions (Myers & Swerdloff, 1967). Longevity also plays a role, as it is easier to tear down than to renovate at the final phase of a structure's life, and it is harder to control quality (Tavares et al., 2021).

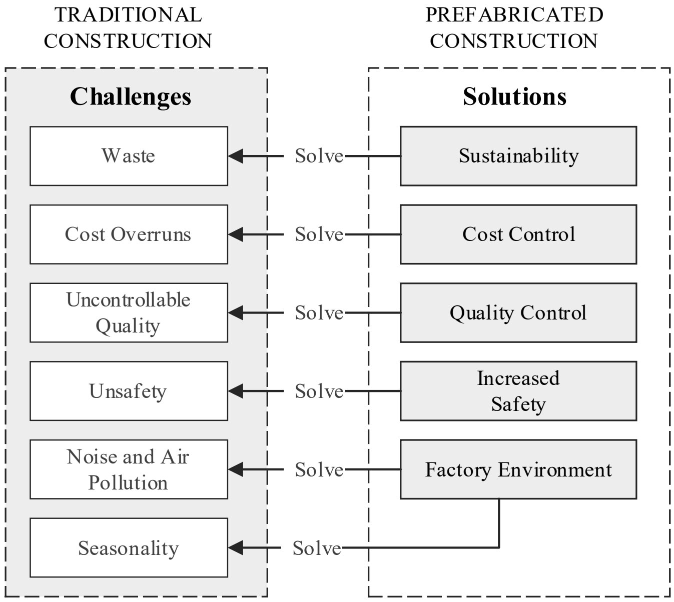

Figure 2: Traditional methods versus Prefabrication

Accordingly, the study suggests using prefabrication or modular construction to address these problems (Figure 2). The advantages of the modular method are quality assurance and predictable outcomes (S. Wu et al., 2022). Due to this factory environment, there is a reduction in noise and air pollution in the surrounding community, a smaller site footprint, and less material stored at the factory. We can work in any weather condition (Wilson, 2019). The costs are also reduced as they decrease by combining factory and site activities. Doing that can reduce the project duration and site assembly time. There is also a reduced labor requirement, which improves productivity (Zadeh et al., 2018). Safety also increases as there is better control of dangers to health and safety in an industrial environment, a 63% overall reduction in safety accidents, and a reduced chance of fall-related injuries (*Chubb North America*, 2020). Finally, wastage reduces as there is 52% less construction waste, 44% less energy consumption, and 9% less contribution to global warming (Z. Wu et al., 2021).

LITERATURE REVIEW

While prefabricated construction has numerous benefits, this practice still needs improvement and has some issues. They need more standardization in the process, which means more familiarity and expertise to implement prefabrication. Prefabrication demands accurate and trustworthy data as well as increasingly automated equipment. There needs to be better communication and coordination than there has historically been. There needs to be more cooperation between builders and their suppliers, and a lack of communication with vendors of off-site prefabrication requires risks of unanticipated expenses and flaws. All supply chain participants and companies should have (Lopez et al., 2022). Traditional construction gives us beautiful and aesthetic buildings, and there is a lot of variety in modular construction that needs more variety because complex designs involve more planning and custom designing. Everything is restricted to what can fit on a truck (Eliwa et al., 2020). Transportation also disturbs the smooth working flow of prefabrication, as difficulties arise from the movement of prefabricated components to prevent storage issues and idle time; fabricated parts need to be delivered only in order to prevent the supply chain from becoming more complex (Stroebele & Kiessling, 2017). Finally, stakeholders need more trust and collaboration because supplier companies typically carry the most risks, and factory follow-ups and performance monitoring are often done improperly. A systematic performance measurement system and real-time analysis are necessary to analyze and continually improve the manufacturing process due to the complexity of prefabrication, the significant number of stakeholders engaged, and the number and complexity of contracts (Chen & Samarasinghe, 2020).

Furthermore, Z. Zhang et al. (2022) successfully reflected the recent changes in the Australian prefabrication industry in particular and explored the benefits and challenges of implementing prefabrication from industrial perspectives globally.

Table 1: Benefits and challenges shared by academia and industry interviews, adapted from Z. Zhang et al. (2022)

	Benefits/ Solutions	Challenges
1	Time saving	Cost inefficiency
2	Better quality	Lack of skilled workforce
3	Energy saving	Lack of standardisation
4	Improved construction safety	Transportation & logistics issues
5	General cost benefits	Misconceptions
6	Reduce on-site work and labour	Inflexible for design change
7	Reduce on-site construction waste	Market demand
8	Addressing skills shortage	Site access
9	Lower production cost	Lifting safety

10	Less disruptive to neighbours	Protection during transportation
11	Relief housing demand	Compliance and inspection
12	Waste recyclability	Lack of automated adoption
13	Material saving	Bankability
14	Light weight of prefab. materials	Moisture control
15	Increase project certainty	Fire, thermal and acoustics testing
16	---	Payment process

Note: Table 1 showed summary results of the industry's perspectives on the challenges of using prefabrication. It provided a valuable reference for all parties in the prefabrication supply chain, to update their knowledge or understanding of the barriers toward widespread adoption of using prefabrication and their corresponding recommendations.

Through a literature review and interviews, Z. Zhang et al. (2022) classified the significant challenges into eight aspects related to feasibility, design, manufacturing, transportation, on-site construction, standardization, skills and knowledge, finance, and market. The authors summarized recommendations to tackle these barriers, particularly in adopting digital technologies in prefabricated construction. The application of cloud-based technology, the Internet of Things (IoT), BIM, and Blockchain, has been proven effective in improving information exchange, reducing uncertainties during logistics, and therefore improving the schedule performance of prefabricated construction. The findings could help local industries and governments develop roadmaps and policies promoting prefabrication. Similarly, Jin et al. (2018) implemented a holistic review approach incorporating bibliometric search, "*scientometric*" analysis, and in-depth qualitative discussion for reviewing and summarizing off-site construction literature published between 2008 and 2018. The authors proposed a framework to link current research areas in off-site construction to future research directions. The study found that sustainability, standardization, safety, and productivity are the performance measurements of prefabrication projects. Supply chain management, standardization, automation, fragmentation, and logistics are project delivery processes for off-site construction, considering the life cycle assessment approach. At the same time, the inclusion of multiple stakeholders and project parties in the design stage of a modular project is regarded as critical in some social and cultural contexts. The readiness of stakeholders to adopt off-site construction within a specific country or cultural context is crucial, as well as global cross-country comparisons. This review-based study provided both academic and practical implications. Scholarly, this study added to the body of off-site construction knowledge by focusing on developing off-site construction research in the last decade.

With the potential of applying digital technologies, the construction industry is at the point of a transformation driven by prefabricated construction. However, based on the detailed literature review, the authors have explored common challenges while implementing prefabricated construction. Some of the identified barriers include (a) lack of design, (b) lack of standardization, (c) poor communication and coordination, (d) transportation and logistics issues, and (e) lack of trust and collaboration among stakeholders.

Generally, the current research on prefabricated construction focuses on improving technology and addressing the barriers to the widespread adoption of prefabrication and its opportunities. The current studies aim to solve the challenges of prefabricated construction by applying BIM and Blockchain technology in different applications. However, combining these two technologies to collectively solve the challenges faced in the widespread application of modular construction is a new approach. Moreover, the values of integration and "*building trust among all the stakeholders*" from integrated project delivery are enforced by involving various suppliers, builders, architects, fabricators, engineers, and transporters right from the beginning. In such a case, the feasibility and duration of each sub-procedure can be accurately calculated.

Also, allowing them to coordinate through a Blockchain setup sets the steppingstone for developing a culture of trust and coordination.

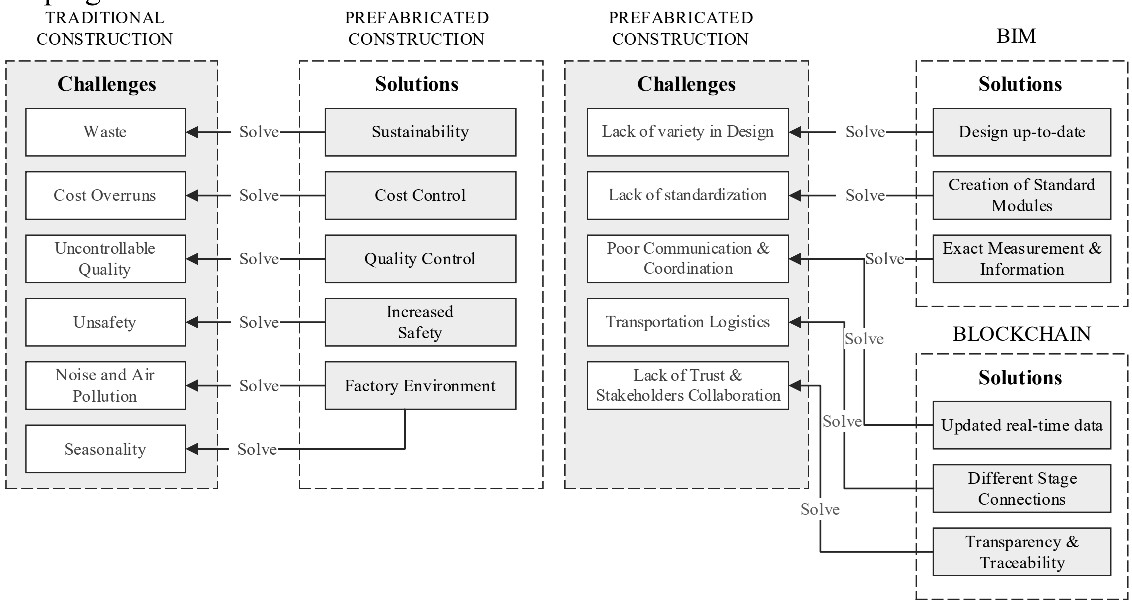

Figure 3: Proposed research conceptual schema to address the barriers toward widespread adoption of prefabrication in literature review.

DISCUSSIONS

Building Information Modeling (BIM) and Blockchain are emerging technologies that have the potential to advance prefabricated construction significantly. In combination, BIM and blockchain have the capability to greatly enhance the efficiency, quality, and transparency of modular construction, leading to improved outcomes for construction stakeholders. By leveraging these technologies, prefabricated construction can become more reliable, efficient, and cost-effective, making it a more sustainable option for a broader range of projects.

This section presents the relevant data found in the literature on the uses of BIM and Blockchain to aid the problems commonly raised in the prefabrication method.

BUILDING INFORMATION MODELING (BIM)

Originally, it took a remarkably long time for BIM to displace its predecessor, which at first started with hand-drafting, computer drafting, computer-aided design (CAD), and other computer-based systems. BIM is technically designed to increase information integration among project stakeholders significantly. Integrated information is the foundation and the source of integrity and insight, which allows an integrated team to make the best decisions for the project. By using visualization as a platform, BIM can help an integrated team create the aesthetics of a design and interpret the values of the building's owner and end users. Simulation is another primary use of BIM, which allows teams to evaluate alternative designs and strategic interventions to reduce risks and negative impacts. In addition to monitoring the initial cost, the team can now analyze energy consumption, workflow, natural light, and previously unmeasurable values like "*openness*" and "*connectedness*" (Martin Fischer et al., 2017). The Architecture, Engineering, and Construction (AEC) industry continues to push forward to build quicker, smarter, and more efficiently. As a result, using BIM has become crucial to achieving these goals of creating structures in a shorter timeframe while maintaining safety and sustainability. BIM is used in the world of prefabrication to make this construction more precise and efficient. While prefabrication has its issues, such as a lack of variety, standardization, and communication, BIM can be used as an effective method to ensure these issues are addressed and avoided.

BIM offers the unique ability to design with the intention of prefabricated, allowing for designs to be specified and designed around how they are to be sent directly to the shop and then from the shop to the site (Jang & Lee, 2018). In most cases, construction projects include errors only discovered once they are already on site due to a lack of communication between the AEC parties. Using BIM, these errors can be discovered quickly and designed in a way that they can visualize the building components, identify clashes, and then create shop drawings that either compensate for or fix the issue. This saves a tremendous amount of money in the later stages of construction when time is a crucial aspect of the project. To truly earn the benefits of BIM in prefabrication, the total collaboration between the architects and subcontractors is crucial to creating efficient prefabricated parts that include all the necessary mechanical, electrical, and plumbing (MEP) for the intended prefabricated structure. In the case of the 500,000 ft2 Miami Valley Hospital, a 12-story addition was added using prefabricated modular bathrooms, casework, headwalls, and workstations (*Architecture | NBBJ*, 2012). Architects worked countless hours with different MEP contractors, nurses, managers, and more to find the most efficient design while creating a usable and effective space. It was estimated that using this method increased productivity by 300% and saved more than two months off the 30-month project total. BIM helped achieve these feats by allowing the architects to find ways in which parts of the overall model could be designed for prefabrication and fit onto the truck for transportation.

BLOCKCHAIN

Blockchain has been around for a couple of years; however, its use within the construction industry has yet to be fully utilized. The use of Blockchain within prefabrication offers the AEC industry vital support in notarization-related applications to reduce the time for authenticating documents, transaction-related applications to facilitate automated procurement and payment, and source-related applications to improve the transparency and traceability of construction supply chains (Li et al., 2021). These solutions greatly help reduce typical issues within prefabrication, such as collaboration between multiple parties, shipping planning, and trust/ stakeholder collaboration. The Blockchain is a mode of Distributed ledger technology (DLT) where all the processes of business or construction can be verified and uploaded. It acts as a distribution network where no single authority is needed to maintain the verification of involved parties, giving stakeholders complete access to track construction history and check the recorded data conveniently (Li et al., 2021). Because of its highly trustworthy database, the Blockchain allows massive construction data to be kept impartially; in other words, an extensive range of information may be used in a traceable, secure, and sustainable manner (Li et al., 2021). We can then use Blockchain to create and automate various parts of the prefabrication process. An event completion, whether that be material arrival at the fabrication facility or completion of the fabricated item, would then trigger the next step within the automated contract to begin quality checks, time recording, payments, and so on. Within the supply chain, prefabrication can be difficult in terms of tracking regarding the status of the condition or location of the designated object. Blockchain offers the ability to track smart construction objects (SCOs) through their sensing, processing, and communicating capacities to facilitate information exchange among various construction resources (Lu et al., 2021). By attaching a Radio-frequency identification (RFID) or Quick response (QR) code to these SCOs, we can create checkpoints along the supply chain that automatically track these objects and update the Blockchain contracts with relevant and accurate data regarding the positioning and status of prefabricated items. Figure 4 shows a detailed SCO plan for construction processes with two types of models (Lu et al., 2021), which are model 1: a low-energy, single GPS sensor for location-based service in off-site logistics and model 2: high-frequency multiple motions and environmental sensors for off-site production and on-site assembly.

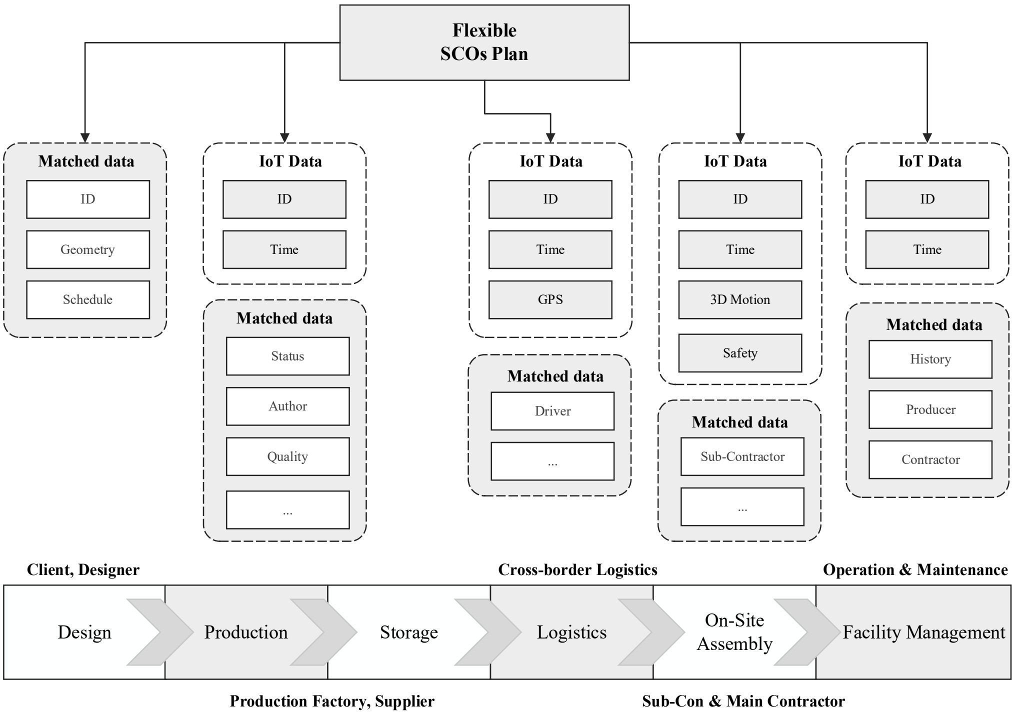

Figure 4: An SCO plan for construction processes: Off-site production, logistics, and on-site assembly services, adapted from Lu et al. (2021)

RESULTS & FINDINGS

The challenges or barriers mentioned earlier still exist in the prefabricated construction method. Figure 5 below illustrates how each of those five issues could be solved by implementing an integrated approach using BIM and Blockchain technologies during the prefabrication process.

First, the lack of variety is caused by complex designs requiring more planning and custom design with size restrictions so that the prefabricated fragments can fit in the truck for transportation (Eliwa et al., 2020).

Second, the lack of standardization in the prefabrication process demands more precise and trustworthy data, as well as more automated machinery (Rose Morrison, 2021). There is also a need for more familiarity and expertise in implementing prefabrication because workers need to be able to create documents accurately and efficiently. Using BIM helps analyze constraints to give maximum efficiency in designing project fragments that can be prefabricated and fit on a truck. It allows for the prefabrication of sophisticated systems such as irregular exterior paneling and MEP modules (Jang & Lee, 2018). BIM helps analyze the exact data, providing the exact measurements of the fragments the subcontractor requires for module prefabrication.

Third, poor communication and coordination are common among builders and their suppliers. BIM reduces discrepancies in a final model among both designers and manufacturers, shrinking the procurement schedule as an embedded BIM execution plan can facilitate design cooperation from the start of a project and any required adjustments or modifications on a model that can be incorporated before the proper production phase without adversely affecting the project and product duration and quality (Mostafa et al., 2020). Also, to aid the poor communication and coordination among stakeholders, Blockchain technology allows multiple shareholders to obtain smart connected product (SCP) status data in real-time while linking various stages, responding quickly to worrying occurrences, and reducing energy consumption (Li et al., 2021). Furthermore, by combining Physical asset tracking (PAT), Digital asset management (DAM), and Distributed ledger technology (DLT) contracts through apps, industry partners may leverage a variety of (current or unique) asset tracking and management systems and link them to smart contracts and Blockchain technology (van Groesen & Pauwels, 2022). Organizations are able to pre-set prerequisites on the Blockchain that allow customers to effortlessly engage in the Smart product-service systems (SPSS) chains for (1) notarization-related implementations to shorten the amount of time required for document authentication; (2) money transfer applications to support automated sourcing and payment; and (3) authenticity applications to enhance the traceability and transparency of construction supply chains (Li et al., 2021).

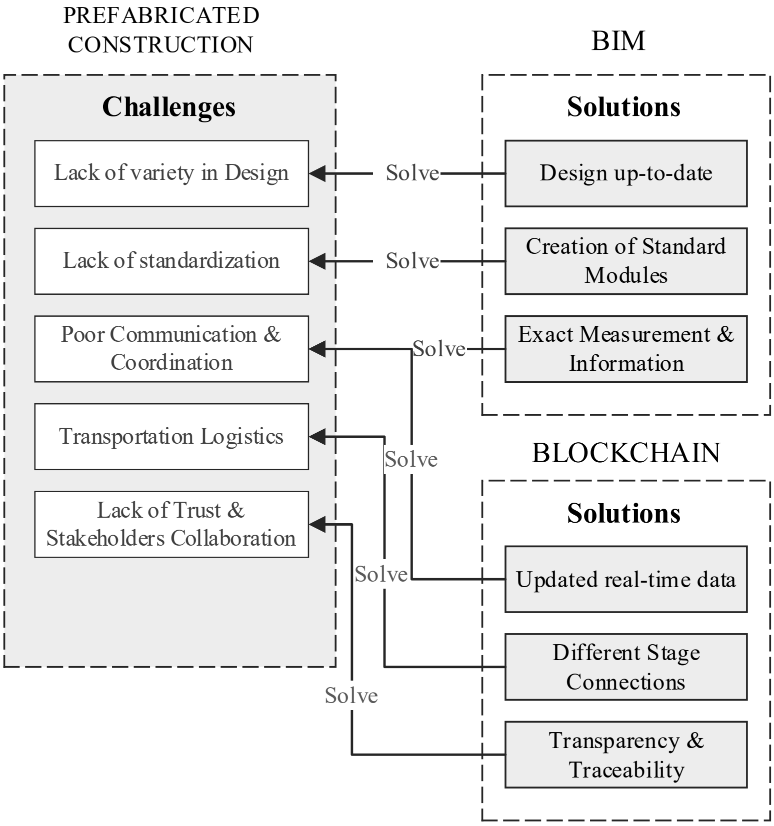

Figure 5: BIM and Blockchain technologies to aid Prefabrication challenges.

Fourth, transportation logistics in the prefabrication process are essential given the difficulties of transporting prefabricated components, such as reduced waiting time and warehousing concerns since the fabricated parts must be shipped just-in-time to prevent further intricacy within the actual supply chain (Stroebele & Kiessling, 2017). Lastly, the lack of trust and collaboration between stakeholders is quite common in the prefabrication construction method, given that, typically, supplier firms bear most of the risks and the need to effectively handle performance appraisals and follow-ups in the production process. The number of complex agreements is also impressively large due to their intricate nature and the many stakeholders engaged in prefabrication. A precise performance evaluation and real-time analysis system are required to monitor and constantly improve the manufacturing process (van Groesen & Pauwels, 2022). Blockchain technology creates traceability and transparency in a collaboratively managed register; its usage diminishes miscommunications and disputes among relevant parties; and it automates the evaluation of advancement and conformity to contractual responsibilities in arranging individually manufactured parts via geographic data tracking technologies. Additionally, QR Codes may be used to track the status of manufactured elements utilizing a mechanism of *"fabricated," "delivered," "ready for assembly," "assembled," "ready for verification,"* and "*verified*" (van Groesen & Pauwels, 2022).

Apparently, the widespread adoption of BIM has been considered a strategy to accelerate the growth of prefabricated construction following decades of slow advancement in the industrialization of construction (Bimal Patwari and Scott Pittman, 2022). The findings reveal potential solutions when applied to construction projects. BIM can address these challenges and provide technical support for the growth of prefabricated construction. Using Blockchain and Smart contracts in prefabrication improves supply chain transparency and traceability in automated procurement, payment, and document authentication. Thus, the construction industry has benefited from advanced digital technology, and the combination of BIM and Blockchain technology within the construction context will discover more benefits of prefabricated construction presently. It is suggested that BIM will help solve the most significant problems that prefabricated construction projects confront now, such as Lack of design and standardization, poor communication and coordination, transportation and logistics, and Lack of trust and stakeholders' collaboration.

FUTURE RESEARCH

This paper presents the investigations and literature review findings in the prefabrication field of the construction industry. Even though there have been few implementations of Blockchain in the construction sector, the study predicted that there would be significant benefits for latecomers. The many advantages of combining Blockchain with BIM were emphasized. Future research is needed to expand and enhance the application of innovative technologies in prefabrication, such as construction 3D printing (C3DP), Virtual reality (VR), Augmented reality (AR), and the Digital twin (DT). In addition, several current techniques or approaches are being considered for the integration of advanced technologies into prefabricated construction, such as Cloud-based computing, which stores data generated by BIM; integration platforms like BIM360; collaborative workflows as Integrated Project Delivery (IPD); Machine learning, and Artificial Intelligence (AI) which are being used to automate and optimize processes. Developing and implementing new technologies in the prefabrication industry that address supply-chain issues, safety concerns, and management challenges is necessary. There should be a need for suitable research methodologies to integrate various other technologies to ease the use of prefabrication in the construction industry, keeping the industry's traditional approaches in mind. In general, using advanced technologies in prefabricated construction offers many potential solutions but presents significant challenges that must be overcome to realize its potential fully.

CONCLUSIONS

This research contributes to the body of knowledge by addressing the barriers to the widespread adoption of prefabricated construction projects and developing an integrated approach for applying advanced technologies to the prefabrication process. Our research suggests that an integrated approach combining BIM and Blockchain technologies during the prefabrication process will help solve the most significant problems that prefabrication projects face, such as a lack of design, a lack of standardization, poor communication and coordination, transportation and logistics issues, and a lack of trust and collaboration among stakeholders' collaboration. Together, BIM and Blockchain can help to streamline the prefabricated construction process in terms of design up-to-date, the creation of standard modules, exact measurements, and information, updated real-time data, different stage connections, transparency, and traceability. Most significantly, the approach proposed in our research advanced the prior works by proposing a conceptual schema for addressing each problem highlighted in previous studies. In addition, this research demonstrates how prefabrication addresses challenges associated with traditional construction and how the challenges associated with prefabrication can be addressed through our proposed integrated approach involving technologies. This study benefits professionals and academics by providing a framework for comparative analysis and investigation into the benefits and drawbacks of various approaches. Although modular or prefabricated construction has a long history, adoption remains remarkably slow. After decades of limited development in the industrialization of construction, the widespread adoption of innovative approaches and emerging advanced technologies is now seen as a viable approach to accelerating the growth of modular construction in the near future.

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PRODUCT AND PROCESS COMPLEXITY IN CONSTRUCTION: AN EXPLORATORY STUDY USING BILL-OF-MATERIALS (BOM)

Carolina Melecardi Zani[1] and Cecilia Gravina da Rocha[2]

ABSTRACT

Modularity has been applied in the automotive and computer industries to simplify production and supply chain management. Instead of coping with dozens of hundreds of parts, these are grouped into modules produced and delivered by suppliers, simplifying products assembly. Bill-of-Materials (BOM) is a technique used in manufacturing to map the modules that form a product at distinct hierarchical levels. Yet, to the best of our knowledge, such technique has not been widely explored in construction to assess the complexity involved in buildings production. This paper uses BOM in an empirical case (a house of approximately 400 square meters built in Southeast region of Brazil) to analyse (i) the total number of different modules forming a building and (ii) how these modules are distributed throughout the work packages for producing such building. The results show that the studied house is formed by (at least) 522 different modules, which are unevenly distributed across 18 work packages. Some work packages (e.g. concrete pillars and walls) have more than 200 modules whereas others (e.g. foundations) have less than 10. This suggests the potential for repackaging and organizing the delivery of modules as kits to ease production tasks.

KEYWORDS

Complexity, modularity, modules, work packages, work structuring

INTRODUCTION

Simplifying production and supply chain management is a core underlining reason for the adoption of product modularity in the manufacturing sector. Instead of coping with dozens of hundreds of product parts these are grouped into modules (sets of parts), which are produced and delivered by suppliers, simplifying the final product assembly. Baldwin and Clark (1997) report that the complexities of a vehicle require car manufactures to control a network of hundreds of suppliers in addition to a complex schedule and a large inventory as buffer. Thus, instead of managing the entire network of suppliers for producing each individual part, parts are organized and delivered as a smaller set of modules (e.g. Doran et al. 2007; Ro et al. 2007). An example is the cockpit module that includes several parts (air bags, heating and air-conditioning systems, etc), which is produced and delivered by a supplier responsible for coordinating the chain of suppliers involved in producing this module (Baldwin and Clark 1997).

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Bill-of-Materials (BOM) describes the structure of a product in terms of its constitutive parts (termed here as modules) with the goes-into-relationship (also known as a parent-child relationship) among them (e.g. Chung and Fischer 1992, Cox et al 1992, Olsen and Saetre 1998, Matías et al 2008, Kashkoush and ElMaraghy 2016). BOM can be used to assess the extent to which the modules delivered are more or less aggregated and also the number of hierarchical levels that comprise a product architecture. Indeed, as recognized in the literature, modularity of a product and its constitutive modules can be analysed at distinct hierarchical levels. For example, Fixson (2005) examined such hierarchy from a functional viewpoint (namely, the functions performed by the product parts). He argues that the function of a hair dryer (the set of all components forming the product) at the highest level is to dry the hair whereas at the lowest level (of a single part such as screw), might be to hold part B in position C. Thus, not only functions (but also the corresponding physical parts or components performing then) can be analysed at distinct levels.

Inspired by the manufacturing industry, the construction sector has adopted information structures relying on BOM (Hussamadin et al., 2020). Most papers on the construction field related to BOM address (i) Building Information Modelling (BIM), or other technologies, to BOM management (e.g. Zhang, 2022; Song and Fischer, 2020; Mukkavaara et al., 2018; Boton et al., 2018; Song et al., 2017; Genge et al., 2015; Scheer et al., 2014) or; (ii) BOM focused on construction sustainability, such as life cycle assessment (e.g. Tavares and Freire, 2022; Roh et al., 2019; Zea Escamilla and Habert, 2017; Al-Ghamdi and Bilec, 2017) circular economy (e.g. Gillott et al., 2023), replacement of materials (e.g. Ortlepp, 2019; Zea Escamilla and Habert, 2017; Milaj et al., 2017), and other topics (e.g. Songcayauon, 2018; Winistorfer et al., 2005). Yet, these studies do seem not examine BOM from a product modularity viewpoint and their implications from a product and process complexity.

This paper seeks to address this gap by presenting an initial exploration on this theme. It aims to provide initial answers to the following questions: *How many modules (or physical chunks) form a building? How are these modules distributed throughout the work packages? What insights can be gained by connecting the modules forming a building (product view) to work packages (process view)?* In line with Da Rocha and Kemmer (2018), modules (identified in this study by applying the BOM technique) and work packages, refer respectively to the organization and breakdown of (i) a product and (ii) a construction process. Work packages are the outputs of work structuring, and define the organization of work chunks (namely, in what chunks will work be assigned to a production unit, release to the next production unit, in what sequence, etc) as detailed in Ballard (1999).

BILL-OF-MATERIALS

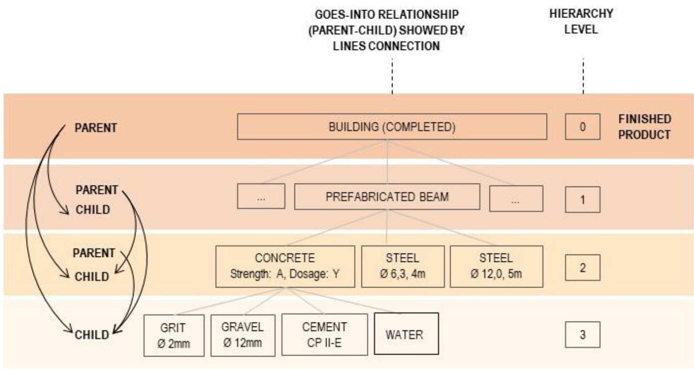
All modules that form an end product pertain to a hierarchical level, or in other words, every product can be decomposed into modules, which can be further decomposed into lower levels modules (Pahl and Beitz, 1996). The level to be considered can be defined according to the assembly sequence or the function performed by the modules and how it relates to the end product (Chung and Fisher, 1992). The hierarchical level is higher as it gets closer to the final product and its main function; therefore, the highest level is the entire product. The notion of decomposing a product in hierarchical levels has been presented in a number of early studies (e.g. Alexander, 1964; Christensen, 1992; Gulati and Eppinger, 1996; Simon, 1962). A technique that maps the assembly sequence of a product (and thus, the modules comprising such product at each level) is the Bill-of-Materials (BOM) (e.g. Chung and Fisher 1992, Van Veen 1992, Jiao et al 2000). In its simplest from, the BOM is a list or a visual display (e.g. tree map, fish bone diagram, list, etc) of all modules (raw materials, components, sub-assemblies, etc) needed to produce an end product.

The modules and how these should be connected are presented through goes-into-relationship (or a parent-child relationship). The “parent” is an (i) in-between product (grouping of modules at a particular level) or (ii) the end product, and the “child” are the modules forming either one of these. For example, in Figure 1, “prefabricated beam” (at level 1) is a parent for all the subsequent modules (at levels 2, 3, etc). “Concrete” is a child for the “prefabricated beam”, but also a parent for “grit”, “gravel, “cement” and “water”. Note that “grit”, “gravel, “cement” and “water” are also a child for the “prefabricated beam”, but in a lower hierarchical level. Figure 1 shows the parent-child relationship in list (a) and tree (b) formats. In the former such relationship is elicited via codes (numbers), whereas in the latter it is through lines connecting the modules at distinct levels. Such codes are not often used in trees representations (Van Veen, 1992). Yet, numbers are usually included to express the volume of modules at each level (Erens et al, 1992; Hegge, 1992; Van Veen and Wortmann, 1992; Stonebraker, 1996; Romanowski and Nagi, 2004, Liu et al, 2014). Distinct information elements can be presented in a BOM such as product definition, manufacturing instructions, engineering changes control, service parts support, liability or warranty policy, order entry facility, costing, and pricing (Mather, 1987). Yet, such technique can also be adapted as needed. Here it is used to map the number of different modules (but not volume) at levels 1 and 2, considering the building assembly or finished product (level 0).

GOES-INTO RELATIONSHIP (PARENT-CHILD) SHOWED BY NUMBERS

HIERARCHY LEVEL	MODULE CODE	MODULE NAME	QUANTITY
0	000000	BUILDING	
1	011000	PREFABRICATED BEAM	
2	011210	CONCRETE	
2	011220	STEEL Ø 6,3	
2	011230	STEEL Ø 12,0	
3	011231	GRIT	
3	011232	GRAVEL	
3	011233	CEMENT	
3	011234	WATER	

a



b

Figure 1: Example Bill-of-Materials as list (a) and tree diagram (b)

To illustrate the applicability of BOM in the construction sector, two examples from the literature are explored comparing BOM off-site (e.g. prefabricated components), more similar to the manufacturing sector, and BOM on-site, which is further developed by this paper. Cao et al. (2022) explore the advantages of BOM combined with BIM, in industrialized construction. Industrialized construction has high degree of repeatability and standardization, such as hotels, affordable housing, schools, hospitals and so forth (Bertram et al., 2019; Cao et al., 2022). This enables a trustful BOM, which in turn enables reliable management of resources. The referred authors propose a module library, using as a timber panelised building as an example. They argue that BOM is the key to information system, offering data with regards to designing, ordering, building developing, construction and maintenance. The BOM complements the BIM application, since BIM by itself is not capable of automatically manifesting the effect of a design change, unless the change violates a rigid constraint, such as a clash.

On the other hand, Hussamadin et al. (2020) highlight that construction is an ongoing process, unlike the assembly line in manufacturing production, in which new spaces are becoming available while work is being finished, leading to a more complex and dynamic relation between such process and the BOM. The authors explore five construction assets in three construction companies, showing that among the variation in workflow, more specifically, the space as the non-movable component, is a challenge of applying BOM to on-site construction and which makes the applicability of BOM more complex. Their study proposes some adaptations of such tool, highlighting the relevance of studies that adopts BOM applied to in-site construction, such as this one. Both studies (Cao et al., 2022 and Hussamadin et al., 2020) show that the complexity of the products (hereby understood as a high number of modules present in the final product) and assembly system can be assessed by the BOM. Such tool can provide support to management decisions by showing where the source of complexity arise from and help to rationalize the choice of product features and design alternatives. BOM involving can help assess complexity a priori without the need to for detailed information on the constructive system but instead just by looking at the number of modules across the BOM structure.

CASE STUDY

This investigation examined the budget sheet and the production schedule for House A developed by Company B, based in the city of São Paulo (SP), Brazil. Company B has been operating since 2001 and has delivered more than 200 buildings. Most of these are residential houses, but there are also some high-rise buildings and industrial sheds. The company provides a complete solution: it is involved in the product development, including the building design, its production and hand over to the end client. The majority of production tasks are performed by Company B but some such as the foundations and the water heating system are outsourced.

Company B is comprised of an average of ten teams with ten people each. Each team gets a different building to work on which are then swapped across teams. Usually, three people work in the office (the interns work both at the office and at the construction site) and seven in the construction site. The project coordinator, the civil engineer, and a construction coordinator work at the office but visit the construction site regularly. In the construction site are the electricians, hydraulic professionals, painters, etc.

Initially, Company B suggested three houses for this study. House A was selected because it had the most complete budget sheet and had been recently delivered at the data collection time, thus easing potential queries and clarifications around the information gathered. House A is a four-bedroom home with approximately 400 square meters. Besides the common amenities of a house, it also includes parking space for four cars, a gourmet area, a courtyard, and offices. This building was erected using traditional construction methods: cast in place reinforced concrete and ceramic bricks. The construction took place between May 2013 and April 2014.

DATA COLLECTION AND ANALYSIS

First, the budget sheet for House A was sent by Company B via email for its appraisal and assessment. An initial analysis showed that some modules were missing, so receipts for all purchases were requested. These were organized and added to the budget sheet. The first author then performed a one-week visit to the company. During this visit, a one-hour meeting was conducted by the first author with the director, the civil engineer intern, and the building contractor to gather data on the production schedule for House A. Additional receipts and purchase invoices were provided and tabulated, creating a complete budget sheet that produced the results presented in this manuscript.

A second meeting with the same staff was performed to gather data on the company, further details on the production schedule, and to clarify queries regarding some items of the budget. This meeting lasted one and a half hours. The production schedule devised by the first author was based on the realized tasks and actual durations, rather than plans and expected durations previously established by Company B. Thus, the work packages presented here were defined by the authors mainly based on the data gathered in the meetings, the duration of tasks, trades similarities, and crew changes.

RESULTS

The BOM (based on the complete budget sheet) shows that House A is formed by 522 different modules. Considering that a BOM is comprised of several hierarchical levels, the highest is the complete building (finished product), and the modules (or physical parts) arriving at the construction site (522) are located in level 1. Such number (522) does not entail repetitions (or quantities) for each module, which would be a subsequent step in applying the BOM technique. Some examples of modules include: nail (15x15), cement tile (2,44x0.5 x 4mm), steel bar (CA60 4,2mm 12m), rafter (5x5cm x 2,5m made of cambara wood), batten (2,3x7cm made of cedro arana wood), and batten (2,3x15cm made of cedro arana wood), among others. It is worth noticing that elements that have the same of function (e.g. batten) but have different dimensions (e.g. 2,3x7cm or 2,3x15cm) are treated as separate modules as they are physically different chunks. It is worth noticing that although BOM might resemble Work Breakdown Structure (WBS) in terms of the underlying logic (i.e. a systems' organization in terms of its constitutive parts), the former is specifically focused on the products and its comprising physical parts whereas the latter is more broadly applied to projects and its key stages.

Figure 2 shows the distribution of the 522 modules across the 18 work packages identified in the production schedule for delivering House A. Some modules such as nails, pipes, electric conduits, are used in more than one work package. Thus, the sum of modules in all work packages is 1020 and not 522 (in case each module was used in only one work package). There is an average of 57 modules per work packages yet with a high standard deviation as can be visualize seen in Figure 2. For instance, *WP1 – foundations* has 6 modules whereas *WP5 – concrete pillar and slab (2nd floor)* has 223 modules. Approximately 70% of the work packages have less than 50 modules, with the other 30% (concrete pillars and walls for both floors, fixtures and fittings, and electrical and hydraulic systems) have more than 150 modules. These four work packages (WP3, WP5, WP10, and WP17) account for 76% of the total number of modules. WP3 and WP5 have a large number of modules because rebar and wires arrive as separate items (rather than cut, folded, and pre-assembled kits for columns and beams). In addition, the pipes embedded in the walls also arrive as individual components rather than pre-assembled kits. The same applies to electrical and hydraulic systems; all wires and pipes are also delivered on site as separate components.

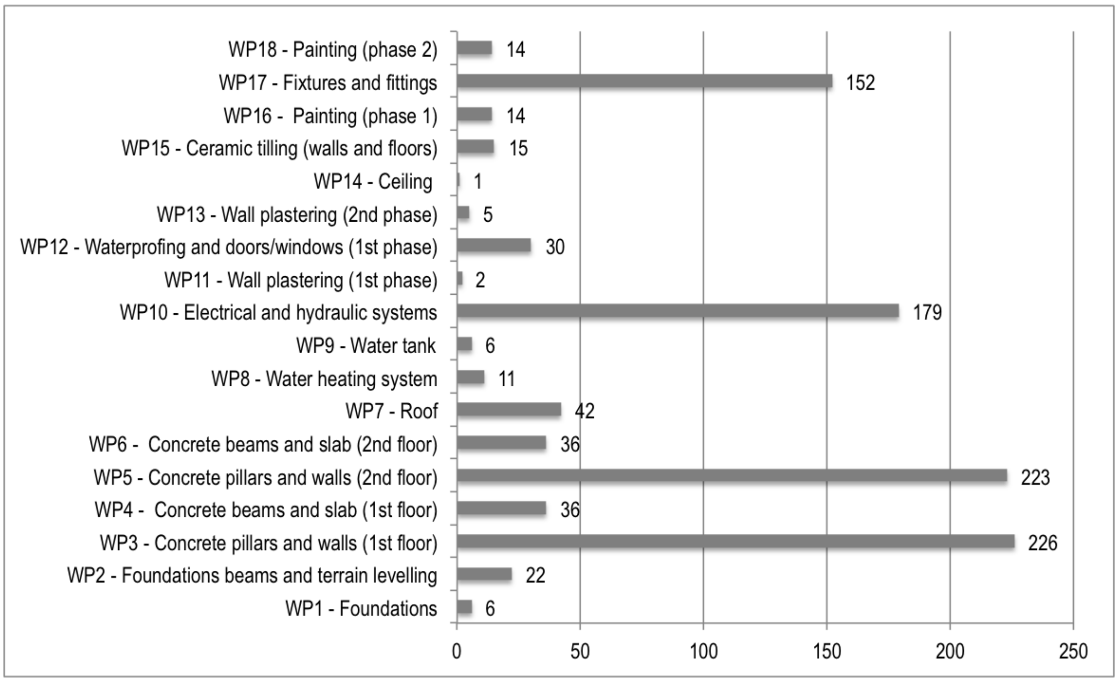


Figure 2: Distribution of modules for House P across the work packages

The 522 modules presented in Figure 2 are level 1 of a BOM (Figure 1), as they are the level immediately below the complete product (level 0) and which refers to the parts arriving at the construction. In this study, the modules at the immediately subsequent hierarchical level (2), namely, the number of parts (or sub-modules) forming each module at level 1 were also analysed. Table 1 shows the number of modules that are formed by two, three, four and five or plus sub-modules at level 2. Because House A is built using traditional construction methods, thus using concrete, steel, wood, bricks, etc (different strength, type, size, etc would be considered modules), the vast majority (79%) does not have sub-modules at levels 2 and below. Indeed, as shown in Table 1, less than one third of the modules is a sub-assembly, namely, has two or more modules at level 2 or below.

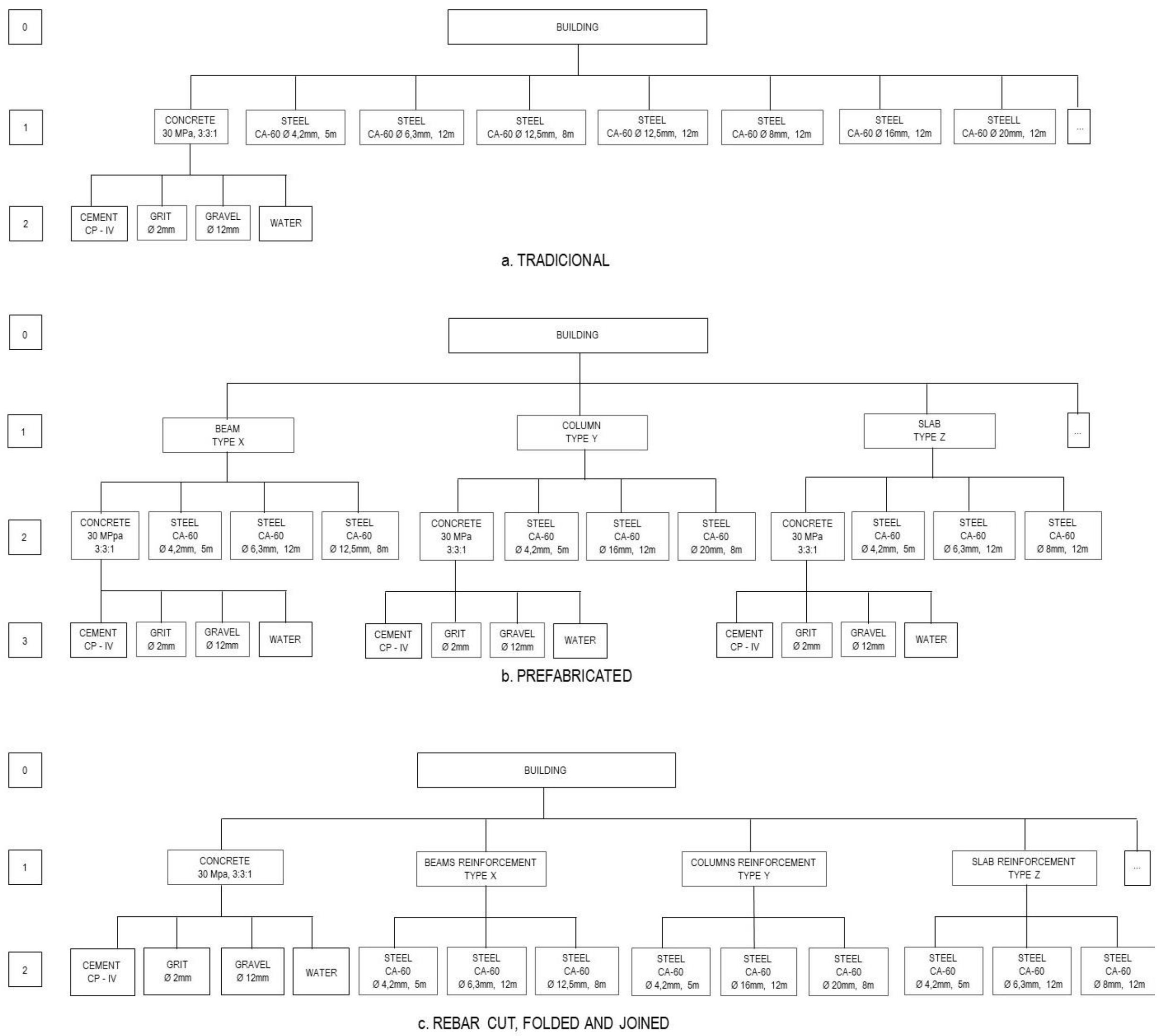


Figure 3: BOMs reflecting different construction methods

Differently, buildings erected using a prefabricated structural system (beams, pillars, and slabs produced off site) such parts (beams, pillars, etc) would be the modules at level 1, and concrete and steel would be modules at level 2 (Figure 3b). this would reduce the product complexity delt with at the construction site, measured by the number of modules at level (building assembly/erection on site). Opting for prefabricated steel reinforcement would result in a in-between alternative, with a smaller number of modules in level 1 in comparison to traditional construction (Figure 3a): steel parts and concrete would still be at level 1, but with a smaller number of different modules at this level (Figure 3c). This is because the steel elements would already be grouped into kits, such as reinforcement for beam X, Y, reinforcement for column A, B, etc instead of individual rebars.

Table 1: Percentage of modules at level 1 formed by 1, 2, 3, 4 or 5 or more modules (level 2 or lower)

Number of modules (Level 1)	Number of modules (Level 2 or lower)
411 (79%)	zero
10 (2%)	two
20 (4%)	three
5 (1%)	four
76 (14%)	five or more

DISCUSSION

The total number of different modules delivered at a construction can provide evidence of complexities in terms of product and process (on site production and supply chain). These can be further understood by assessing how these physical chunks are structured and organized by using the BOM technique and linking those to the work packages. This study seeks to introduce a notion already adopted in manufacturing (Baldwin and Clark 1997): to partition a product in modules (or production cells) to simplify production. Indeed, what constitutes a module is determined by the supply chain and the production system arrangement. Namely, a cockpit (and its constitutive parts) is a module (from the car assembler perspective) because it is delivered as a single part (or sub-assembly) to the car assembly plant. Thus, the number and nature of modules that arrive the construction site are tangible manifestations of a production system and supply chain arrangement, regardless of if the decisions around such arrangement have been formally made or not. Such rationale and notions seem underlined when considering prefabrication or modern method of construction.

Yet, they also apply to traditional construction even if the physical chunks are simple materials such as concrete, steel reinforcement, etc as in the case examined here. Indeed, this does not seem to be considered more broadly in construction as also noticed in Da Rocha and Kemmer (2018) under the Modular and Traditional design approaches. Based on the results of this exploratory study, the work packages for producing the structural, hydraulic, and electrical systems contain a large number of modules. These are prime candidates to be delivered as kits or sub-assemblies (rather than as a large set of different parts) to ease and simplify construction on site. This is in line with the principle to simplify by minimizing the number of (product) parts (Koskela 2000). A similar analogy was reported by Feloni (2014) when analysing the LEGO Group in the early 2000s. The number of piece types increased from 6,000 to 12,000 and nearly bankrupted the company ("a nightmare of logistics and storage"), meaning that every LEGO module was so unique that they no longer could be considered a module. In order to save the company, they went back to the previous 6,000 pieces. Therefore, in the construction context, precast elements (beams, columns, or slabs) could be used to reduce the number of modules at the construction site (Figure 3b). Also, pipes could be combined into pre-assembled piping systems.

Fitting and fixtures, which also account for a large number of modules, might not be delivered as sub-assemblies if the building is erected using traditional construction methods. Nonetheless, they can be organized and packaged as kits. For example, having a package with a mix of all the fitting and fixtures modules installed in a given room, rather than stocks organized based on the module type (e.g. stock of sinks, stock of tiles, etc). These alternatives just described (creating pre-assembled pipping systems and per room/zone packing of fittings and fixtures) look at re-organizing the product structure (which can be visualized using a BOM) to simplify production. The counterpart strategy is to re-organize the process, or in other words, to (re-)structured the work packages (e.g. Ballard 1999, Tsao et al 2000). For example, WP3, WP5, WP11, and WP17, which entail the assembly/combination of large number of modules, could be disaggregated in two or more work packages. This would enable the number of modules to be more evenly distributed across production units (i.e. a crew performing a set of production tasks, Ballard 1999) and work chunks (i.e. unit of work handed off from one production unit to the next, Ballard 1999). Clearly both strategies (product and process) can be jointly applied to reduce the number of modules and consequently production and supply chain/logistics complexity.

There seems to be an inverse relationship between (i) the number of modules at level 1 in the BOM and (ii) the number of modules in level 2 and/or lower levels, if one assumes a building is made by a constant/same set of modules, just changing their distribution across the BOM levels. In this study, there is a large number of different modules at level 1 in the BOM so these are not likely to be formed by several modules in level 2 and/or lower levels. This is indeed the case (Table 1): 79% of modules (level 1) are comprised of two or more modules in (level 2 or lower). Conversely, for fully modular buildings (e.g. formed by a small number of volumetric pods) there will be a small number of large modules (i.e. pods), which in turn are comprised by a large number of modules at lower levels. However, it is proposed here that an inversely linear relationship between number of different modules and the level of aggregation of physical part into sub-assemblies (or level of prefabrication) might not apply (Figure 4). Considering the case of a load bearing building erected with bricks, the number of modules for the enclosure system might be close to one (if only a few brick types are used for the entire system). The number of different modules is likely to increase if the system changes to a steel structure and dry walls, as a larger set of different physical parts is needed. Clearly, as the level of prefabrication increases and the building is delivered as a set of fully volumetric pods, the number of modules reduces again (right hand side of Figure 4).

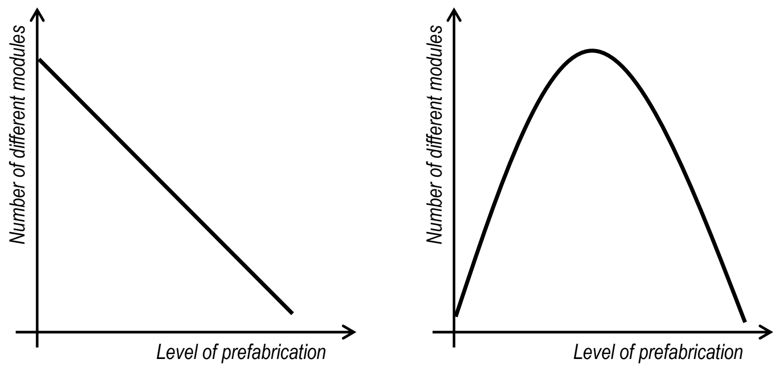


Figure 4: Linear and quadratic functions for

BOM can be used to understand a product breakdown thus also reflecting the complexities involved in operations (procurement, logistics/transport, and on-site construction/assembly). In terms of on-site activities, Tommelein (2006) presents the benefits against the detriments on adopting a modular approach on pipe spool models, which can be generalized for many other components in construction (e.g. doors and windows of various dimensions, supports and fixtures of different types, left- and right-handed mechanical equipment). The referred study shows that as the number of different spools pieces decreases, the production process gets easier. There is potential to a reduction on defects (and thus in rework) with the experienced acquired on repetitive work; there is less time needed to setup and change-over the production of spools; there is opportunities to facilitate flow, by applying the 5S, using right-sizing equipment and lining up work; inventory and supply chain management is also facilitated through the provision of flexibility in the system. These improvements particularly in terms of overall benefits to the system are created by adopting a modular approach.

Aligned with this finding, a previous study developed by MacDuffie et al. (1996) in the automotive sector shows that the disadvantages due to a lack of modularity goes beyond the costs: in such case greater scope of products variants and options have a significant adverse impact on total labour and overhead hours per produced car, assembly line downtime, minor repairs and major reworks, and inventory levels. In this work, they analysed 70 auto assembly plants worldwide. Further, Su et al. (2010) investigated assembly defects caused by operators mistakes by considering complexity factors such as design. The more similar, or modular the product, the fewer are the mistakes. In the manufacturing, the impact of high levels of product variety on complexity in design and manufacture has been explored through different lens (Roy et al., 2011; Samy and ElMaraghy, 2011; Hasan et al., 2018). This resonates with the findings by Fisher and Ittner (1999). The authors examine the impact of the variety of products on car assembly. The results indicate that the larger the number of modules, the greater the risk of errors, resulting in rework and low quality, mainly due to clustering errors and labour difficulties.

CONCLUSIONS

This paper presents an exploratory application of BOM in construction to assess the number of modules forming a building and how these are distributed across work packages. The results show that House A which is traditionally built is comprised by 522 different modules and that these are not evenly distributed across work packages. Most work packages have less than 50 modules whereas a few have more than 150. As discussed previously discussed, the number of modules seems to be closely connected to the method used and traditional construction might not lead to the highest number of different modules. This is because the modules are essentially simple raw materials or components that can be arranged and adapted in a number of different ways. This prompts an interesting discussion: bricks might be positive from a flow view, by minimizing waste associated with finding the correct part, errors in installing the wrong parts, etc as reported by Tommelein (2006). Yet, they are inefficient from a transformation viewpoint as walls are made by assembling small physical chunks, and which often require cutting and adjusting. On the other hand, a steel structure and dry walls system (proposed as an alternative to the brick system), might have opposing trends for the flow and transformation views just described. Fully volumetric pods on the other hand, seem to reconcile the two views by reducing waste relating to non-value adding activities while also ensuring that transformation is efficient.

This is an initial study looking at BOM and how this technique can be used for assessing product and process complexity. (i) The number of different modules (522) as well as (ii) their distribution across work packages (on average 57 but with a high standard distribution with most work package having less than 40 and some more than 150 modules) are relevant metrics in that regard. Yet, such numbers will become interesting in the context of the numbers encountered for other buildings (including other uses and typologies beyond a two-storey residential house examined here) and construction methods so that overall trends and patterns can be identified. In this sense, this is a truly exploratory as additional efforts (studies similar to this one) doing quantifications are needed to create a database for meaningful relationships and generalizable knowledge to be created around product and process complexity. For example, the hypothetical function connecting number of different modules and level of prefabrications could be corroborated or refuted once sufficient data is gathered and large-scale quantifications studies are completed. Another interesting analysis could be performed by collecting the data outlined here in addition to the quantity or volume of each different module (data not gathered in this study) correlated with the project performance measure to further provide insights on the impact of complexity. This would complement and expand the findings presented in Tommelein (2006) based on simulation, by having actual project data (the modules used in a project and its actual performance).

Finally, some limitations of this study should be highlighted. First, Company B did not have a clear production schedule and work structuring. These have been defined a posteriori by the authors. Thus, although care was taken in defining the work packages (use of company data, similarity of trade, etc) as highlighted in section 3.1, more reliable results are likely to be obtained for companies with a formal work structuring and schedule. Secondly, the budget sheet used for House A provided by Company B was not complete and had to be updated by the authors based on invoices. Here again, care was taken in gathering all existing receipts to create a complete budget. Also, the budget was scanned to ensure that main items (concrete, bricks, sink, tiles, etc) were not missing, but it is not possible to unquestionably assert it includes all modules. Thus, as an overall conclusion and ballpark figure, it is more appropriate to state that a two story traditionally built house of around 400 square meters is formed by (at least) 522 different modules.

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FACTORS INFLUENCING CYCLE TIMES IN OFFSITE CONSTRUCTION

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ABSTRACT

In offsite construction, various factors contribute to variability in cycle times at workstations in production facilities, leading to imbalanced production lines. Understanding these factors is vital for implementing Heijunka, a fundamental lean principle that consists of levelling out the work schedule. This study presents a qualitative approach for identifying and understanding factors that influence variable cycle times at the workstation level. The application of the approach is demonstrated in reference to a semi-automated framing workstation in a panelised construction facility. A list of 36 potential influencing factors categorised into eight classes is first compiled based on observation of the process, a cross-functional diagram, and a review of relevant studies, and then discussed based on feedback solicited from personnel at the case framing station through a semi-structured interview. The approach, its application, and the results demonstrate the effect of expending effort on the identification and understanding of cycle time-influencing factors in improving the accuracy of cycle time analysis, thereby facilitating the implementation of Heijunka.

KEYWORDS

Offsite construction, lean construction, cycle time, influencing factors, Heijunka.

INTRODUCTION

MOTIVATION: THE HARE APPROACH

The offsite construction industry, also known as the construction manufacturing industry, is rooted in the broad shift of construction practice from traditional in-situ methods to manufacturing methods. One may intuit that moving towards manufacturing methods will inevitably pave the way for comprehensive and streamlined implementation of lean philosophy in construction. There is a degree of truth to this, as many offsite construction companies have sought to leverage the benefits of lean principles such as standardisation, waste reduction, continuous flow, production line balancing and others with the notable case of a panelised construction enterprise in Edmonton, Canada, applying these principles described in a recent study (Alsakka et al., 2022). Several studies have evaluated the benefits of implementing lean principles in offsite construction, including waste minimisation and workload and workforce density balancing in modular construction (Moghadam & Al-Hussein, 2013; Zhang, 2017), and

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batch and inventory size reduction in precast construction (El Sakka et al., 2016), to name a few. In reality, however, the variable nature and other unique characteristics of construction make the implementation of lean manufacturing practices such as *Heijunka* (i.e., levelling out the work schedule (Liker, 2004)) inherently challenging . As argued by Ohno (1988) decades ago and reiterated by Liker (2004), "*the slower but consistent tortoise causes less waste and is much more desirable than the speedy hare that races ahead and then stops occasionally to doze. The Toyota Production System can be realized only when all the workers become tortoises*." The point here is not to advocate for slow production, but rather for steady production that reduces the likelihood of over- and under-utilisation of resources. The variability inherent in construction projects, however, forces workers and machines in offsite construction factories to follow the so-called "hare" approach. Let us consider, for example, a production line for fabricating wood house walls with one workstation dedicated to framing wall panels and another workstation dedicated to installing sheathing. Since walls are of different types, dimensions, and designs, the time it takes to frame a wall panel or install sheathing, if any, will vary depending on the wall type/design. As a result, if, for a given batch of panels, wall framing takes less time than sheathing installation, the workers at the sheathing workstation will be pressured to speed up their work to keep pace with the framers and keep the production line moving. If this batch is followed by a batch of interior walls for which no sheathing is installed, then the workers at the sheathing workstation will be under-utilised while the framers will be pressured to speed up their work to avoid starving the downstream workstations. In other words, the workers are pressured to function as "hares". Operators in offsite construction do endeavor to reallocate tasks among workstations in order to mitigate this effect, as described in Alsakka et al. (2022), but effective levelling of a production line requires detailed knowledge of the variable cycle times at workstations that is not readily available in current practice.

THE NEED FOR INFLUENCING FACTORS

Given this, researchers have employed machine-learning models trained to consider relevant influencing factors (or prediction variables) in order to estimate process time-related variables. For instance, Shafai (2012)—who argued that average task times should not be used to estimate the durations of highly variable tasks performed for manufacturing wall panels of different designs since the manufacturing time is contingent upon the unique design properties of each panel—built linear regression models for estimating the duration of each task (e.g., spray form insulation) as a function of the given panel's design properties relevant to the task at hand (e.g., number of studs, cut zone area, etc.). In another study, Benjaoran et al. (2004) used multivariable linear regression and neural networks to estimate the duration of production processes in a precast factory as a function of twenty influencing factors such as material weight and concrete strength. However, few studies are available in the literature that have followed this line of thinking for estimating process times or cycle times at the workstation level in offsite construction, although there are studies that have followed this paradigm for estimating other related variables, such as a study estimating man-hour requirements for structural steel fabrication jobs using linear regression (Hu et al., 2015), and another estimating the productivity of steel fitting activities in steel fabrication using artificial neural networks and simulation (Song & AbouRizk, 2008). Moreover, despite the critical role prediction variables play in determining the performance of machine-learning models, the identified studies either have not taken a systematic approach or have not thoroughly discussed the approach followed for identifying the factors that may have an effect on the time variables under study (i.e., task time, cycle time, man-hours, and productivity). The value of expending effort on such an approach is not only that it allows for the relevant influencing factors to be identified; it also helps modellers to gain knowledge about the process under study, in turn allowing them to follow a prescriptive approach for selecting and representing predictor variables (Kuhn & Johnson, 2019). In this manner, they can perform experience-driven modelling alongside empirically-driven modelling, thereby reducing the risk of overfitting to erroneous data patterns or of generating models that cannot be rationally interpreted, compared to an approach that relies solely on empirical data (Kuhn & Johnson, 2019).

STUDY OBJECTIVE AND CONTRIBUTIONS

In this context, there is a need for a structured approach for identifying factors that could influence cycle times in offsite construction. This study thus presents a qualitative approach for identifying factors that influence cycle times at the workstation level in offsite construction factories. The identification of these factors, it should be noted, is an important preliminary step when deploying machine-learning techniques to develop cycle time prediction models as part of the lean practice of production line levelling. The approach is demonstrated through its application to a semi-automated, wood-wall framing workstation in a panelised manufacturing factory in Edmonton, Canada. The study contributions are as follows: (1) shedding light on the significance of analysing cycle times at the workstation level in offsite construction factories; (2) presenting the implementation of a generic approach as a way of encouraging researchers and practitioners to expend effort on identifying the factors influencing cycle time, which are significant for the performance and interpretability of machine-learning models developed to predict cycle times or related process time variables for the purpose of optimising production lines and production schedules (in order to ensure more balanced and efficient production); and (3) providing a preliminary list of factors that could influence cycle times at semi-automated wood framing workstations in offsite construction—a list that could serve as a starting point for researchers or practitioners studying other types of framing workstations.

APPROACH AND METHODS

The study followed a three-stage qualitative approach that leverages the benefits of process mapping and semi-structured interviews to identify the factors exerting an influence on cycle times at a wood framing station. The approach is presented in a generic manner in this section, while the next section describes its application to the case framing workstation.

STAGE I: UNDERSTAND THE PROCESS

An adequate understanding of the tasks involved in a process, the resources allocated to it, the manner in which the tasks are carried out, the process inputs, and of the process outputs enables rapid identification of a number of factors influencing cycle time. Process mapping of the current state, in turn, is an effective means of gaining a thorough understanding of a given process. Process mapping generates an abstraction of the process, allowing for it to be better understood and demonstrated and its performance assessed (Giachetti, 2011). The steps followed in building a process map are described in detail in a previous study by Alsakka et al. (2022). Validating the accuracy of the process map with input from the workers actually assigned to the workstation under study is crucial. The case application described in the present study demonstrates the significance of this validation task. The framing machine is equipped with a cutting saw that is used to cut through the top- and bottom-plates of the panels. Throughout the period of observation that formed the basis of the process mapping, the operator at the framing workstation was manually operating the cutting saw for every wall panel. As a result, moving the cutting saw was recorded as a step in the framing process. However, consultations with the operator revealed that in fact the framing machine was in disrepair, and hence, the operator was manually performing a step that would normally be performed automatically by the machine. In other words, what seemed to the analyst to be a normal part of the process (based on observation alone) was in fact the result of equipment breakdown (i.e., a factor affecting cycle time at the workstation). This example underscores the importance of validating the process map based on consultation with workers on the production line as a crucial step in identifying the factors influencing cycle time.

STAGE II: COMPILE A LIST OF POTENTIAL FACTORS

Based on the results of the first stage, the analyst may identify a variety of factors that influence cycle time at the workstation with regards to various elements involved in the process. The analyst may start by specifying high-level classes that could encompass the different types of factors to be identified, since doing so helps to structure and, hence, facilitate the process analysis task. In this respect, a set of eight major classes is proposed in the presented approach—"product", "worker", "machine", "material", "workstation setup", "production line", "factory operations", and "external factors"—these classes having been preliminarily selected based on the authors' understanding gained during the first stage, then confirmed based on a review of the relevant literature (refer to the Case Application section). In relation to each of these classes, the analyst may identify factors that influence cycle time at the workstation. (Examples of factors that belong to different classes are described in the case application section of this paper.) In addition to the process map, a review of previous research that analyses cycle times, productivity, or related aspects of the process under study, or of similar processes in offsite construction factories, could help to identify additional factors and, possibly, additional classes (over and above the eight classes proposed). At that juncture, the analyst would have a profound knowledge of the process under study and would be well positioned to extract relevant factors from the literature. It is advisable to extract all factors that could potentially have an impact on cycle time at this stage as doing so can further bolster the understanding of the process, even if some of the factors are ultimately excluded at a later stage. The outcome of this stage is a group of classes comprising factors that may impact cycle time at the workstation under study.

STAGE III: SOLICIT WORKERS' INPUT ON THE FACTORS

As the cutting saw example described above demonstrates, the input of workers regarding cycle time-influencing factors is critical, since they are the most knowledgeable about the process. The workers' input may help the analyst to better understand certain factors, highlight significant factors, determine which factors are less important, identify additional factors, or identify relationships between different factors. Hence, upon compiling a preliminary list of factors in the second stage, semi-structured interviews can be conducted to solicit workers' input on the factors in the list. Semi-structured interviews, it should be noted, involve a mixture of close-ended and open-ended questions that are often followed with "why" or "how" questions (Adams, 2015). Semi-structured interviews are valuable when the interviewer (i.e., the analyst, in the context of this study) is interested in the independent thoughts of the interviewee (i.e., the worker) or when there are unknown but potential issues and the interviewer needs to pinpoint beneficial leads and pursue them (Adams, 2015). For each of the identified factors, the analyst may start by asking the worker if the factor affects or does not affect cycle time (i.e., a Yes/No question) and then asking follow-up questions such as "why it affects (or does not affect) cycle time", "how it affects cycle time (i.e., positively/negatively)", and "to what extent it affects cycle time (i.e., significance)". In the case application presented in this study, this approach was found to trigger valuable discussions that yielded useful insights.

Given that a fixed and limited number of workers are typically assigned to each workstation in offsite construction factories, it is possible that some workstations will only have a single worker. This means that there may be just a single worker who is deeply knowledgeable about the current state of the process under study in some cases. However, this would not be critical, as the factors would have been previously identified based on a detailed analysis of the process and previous research work and will be further analysed during the machine-learning process in which the factors will be used. In other words, there are multiple input sources for the factors.

CASE APPLICATION

This section presents the implementation of the described approach on a semi-automated wood-wall framing workstation located in a panelised construction factory. In a recent case study on this workstation, cycle times were found to vary significantly, ranging from approximately 1 minute to about 48.5 minutes (Alsakka et al., 2023). This wide range of cycle times underscores the importance of determining the factors that influence cycle times at such workstations.

STAGE I: UNDERSTAND THE PROCESS

The case framing workstation has a semi-automated wood-wall framing machine that performs three operations: nailing, drilling, and cutting. An operator loads the machine with framing elements when prompted by the machine to do so, and the machine performs the required operations. An automated material feeding system moves studs from their inventory location to a location at the framing workstation from which the operator can directly pull them. The components are made ready half a shift or one shift before they are needed, and are placed on a rack located at the framing workstation in the same order in which they will be required by the framer. Moreover, the top and bottom plates of wall panels are stored on a rack located next to the workstation in such a manner that the operator can directly pull the plates to their loading locations on the framing machine. Figure 1 shows the locations of the different elements.

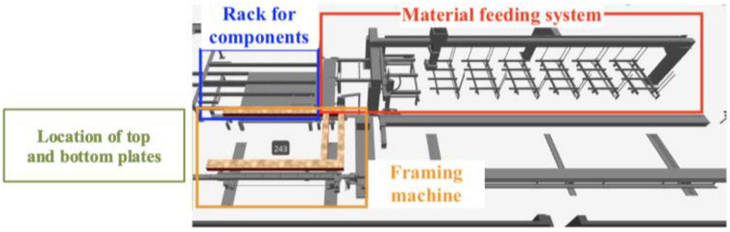

Figure 1: Virtual model of the framing workstation

Given that there are multiple resources (i.e., machine, operator, feeding system) interacting at the framing workstation to frame wall panels, cross-functional diagrams, also known as "swimlanes", were developed to aid understanding as to which tasks are performed by each resource. Cross-functional diagrams, it should be noted, are used to map the workflow of interrelated activities and resources that transform inputs into outputs, as well as to portray the relationships among the various resources performing actions (Damelio, 2011; Giachetti, 2011). A portion of the mapped diagram is displayed in Figure 2. The diagram was first mapped based on observation, and then verified and adjusted based on the operator's feedback.

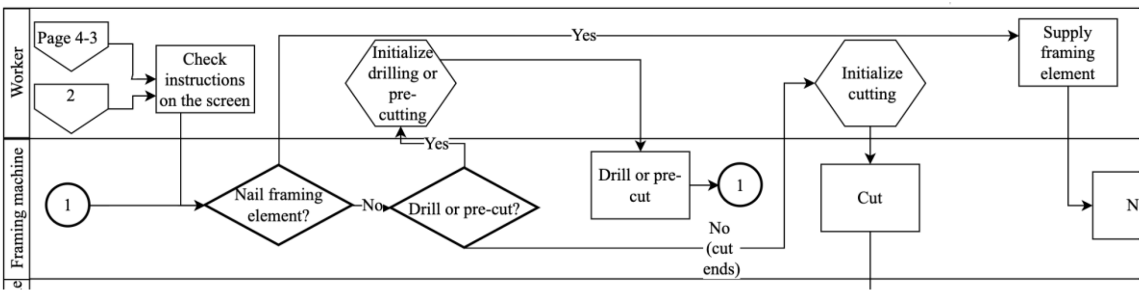

Figure 2: Portion of the framing workstation's cross-functional diagram

STAGE II: COMPILE A LIST OF POTENTIAL FACTORS

For each of the eight classes mentioned above, the factors understood to affect cycle times at the framing workstation were identified based on the authors' understanding gained during the first stage. This was followed by a review of the relevant literature to confirm the comprehensiveness of the classes identified. Because, as previously mentioned, only a limited number of directly related studies were identified, studies examining related metrics such as man-hour requirements and productivity were also reviewed. The factors identified in the relevant literature included, to name a few representative examples, (1) product-related (or design-related) factors such as [length, width, height, surface area,…] for the production of steel panels (Ayinla et al., 2019), [number of single studs, double studs, doors, windows, cut zones, drill holes, nails, screws,…] for the production of wood wall panels (Shafai, 2012), [number of fittings, cut-outs] for steel fitting (Song & AbouRizk, 2008), [number of bolts, length of weld, length of wide flange beams,…] for structural steel manufacturing (Hu et al., 2015), and [nominal height, weight, and width, concrete volume, finishing area, reinforcement weight, concrete strength,…] for precast concrete production (Benjaoran et al., 2004); (2) worker-related factors such as the number of workers (Benjaoran et al., 2004), and skill level (Song & AbouRizk, 2008); (3) material-related factors such as length and weight (Hu et al., 2015; Song & AbouRizk, 2008); (4) machine-related factors such as breakdowns and interactions of material handling systems (Song & AbouRizk, 2008); (5) factory operations-related factors such as work shift (Song & AbouRizk, 2008); and (6) production line-related factors such as activity precedence relationships, queuing, and rework (Song & AbouRizk, 2008). Finally, a list was compiled for 36 classified factors of which the cycle time at the case framing workstation may be a function. These factors are listed in Table 1 below. It should be noted that certain factors that, although may influence framing cycle time, are highly complex and may require a comprehensive analysis of their own (e.g., worker morale, work environment, worker wellness, pay, etc.) were excluded from the case study. It should also be emphasised that, while there may be factors that influence cycle times at framing workstations in other companies, or in other workstations at the case company, only factors influencing cycle time at the framing workstation under study were considered. For instance, the availability of tools and machines is a commonly encountered factor that influences cycle time, but these resources at the case workstation are not shared with other workstations and, hence, are always available. The input of the operator on these factors (presented in the following section of this paper) helps to further clarify meaning, and provide a preliminary justification for inclusion, for the listed factors.

STAGE III: SOLICIT WORKERS' INPUT ON THE FACTORS

At this stage, the operator's input was solicited (via semi-structured interview) concerning the list of potential factors. The operator consulted, it should be noted, has more than ten years of experience working at the framing workstation at the case company, making him highly knowledgeable about the process. The operator was asked whether or not, why (if applicable), and in what manner (if applicable) each of the listed factors affects cycle time. The operator indicated that some of the listed factors are correlated with other factors, which means that they hold information also held by other factors with regards to cycle time. The interview results are summarised in Table (found in the following subsection), where (✓) indicates that the given factor was considered by the operator to influence framing cycle time, (X) indicates that the given factor was not considered by the operator to influence framing cycle time, and (C) indicates that the given factor was considered by the operator to influence framing cycle time, but that the factor is correlated with another one. The operator's comments included in the table are based on written notes taken during the interview. (It should be noted that the comments as represented are a mix of the exact words of the operator and reformulations of some of the operator's input.) Factors for which no specific comments were made during the interview are denoted by a dash symbol in the "operator's comments" cell in the table.

RESULTS AND DISCUSSION

Based on the interview results, the majority of the factors identified in the first two stages were deemed to be relevant based on the operator's input. Accordingly, it was determined that these factors (highlighted in green in Table 1) should be left for the machine-learning process. During the semi-structured interview, the operator provided information that directly resulted in the exclusion of previously included factors, as it became evident based on this information that these factors (highlighted in red in Table 1) do not influence framing cycle time. Removing these factors would help to avoid unnecessary effort expended collecting data on factors that would have been removed during the machine-learning process anyway, as well as reducing the complexity of the machine-learning process. However, factors with respect to which workers may make subjective judgements were not excluded (even when flagged as candidates for exclusion) unless the machine-learning process confirms their irrelevance. For instance, the hypothesis underlying the wall panel design complexity factor is that it may take the operator more time to interpret the shop drawings and load the elements accordingly for more complex wall panels (since they typically require more framing tasks compared to less complex wall panels). Even though the operator indicated that this factor does not affect the time it takes to frame a panel, relying solely on their experience-based input may introduce bias, as it is difficult to assess how long it takes to interpret a shop drawing or load elements from different locations without a quantitative analysis. As such, these factors (highlighted in orange in the table) should be examined in the machine-learning process. Moreover, the operator identified two factors as being correlated with other factors. One of these was panel length (highlighted in yellow), which was indeed found to be correlated with the number of cuts. However, the panel length factor may hold additional information that is not captured by the number of cuts factor or by other factors. In fact, many of the previous studies in this area have used panel length as a factor (as discussed above), further supporting the hypothesis that it is an influencing factor. Additionally, panel length is correlated with the number of holes used for lifting, a consideration that the operator did not mention. This justifies the consideration of panel length as a potential influencing factor, as well as its inclusion in the final list of factors. The other factor identified by the operator as being correlated with other factors was the distance between the nail inventory location and the workstation, this factor being correlated with the nail gun refill factor. Reaching the nail inventory during the process of framing a wall panel was found to be 100% correlated with the nail gun refill factor, and for this reason the former factor can be excluded. Finally, the operator noted that adjusting the machine's opening to accommodate panels of different heights adds an extra step to the framing process for certain panels. Hence, the height difference between a panel and its preceding panel should be examined as an influencing factor. The framing sequence of panels should be also included in the final list of factors to account for any other correlations between cycle times of subsequent panels. Additionally, the operator mentioned that events occurring on certain days may affect productivity (Factor 21). Thus, the framing date should also be considered to better understand cycle times.

Table 1: Results of semi-structured interview

Class	Factors and operator's comments	Effect?
Product	**1. No. of single studs**: - **2. No. of double studs**: "They take more time to nail than single studs as they require more nails." **3. No. of L-shaped studs**: "They also take more time to nail than single studs as they require more nails." **4. No. of multi-ply studs**: "They take more time to nail than the previous three types of studs, and they take more time to nail with every additional ply." **5. No. of regular doors**: "They could take about 6 times longer to nail single studs." **6. No. of large doors**: "They could take about 10 times longer to nail single studs." **7. No. of garage doors**: "I need to do some manual work for garage doors, so they	✓

	take much longer than large doors." **8. No. of regular windows**: "They could about 6 times longer to nail single studs." **9. No. of large windows**: "They could take 10 times longer to nail single studs." **10. No. of cuts**: "Cutting takes about as long as nailing single studs." **11. No. of drill holes**: "The time needed to drill a hole is close to the time needed to nail single studs." **12. No. of blocks**: - **13. No. of components**: -	
	14. Panel length: "Longer panels typically comprise multiple wall panels that are grouped together. As such, they necessitate a higher number of cuts, but this effect is correlated with the number of cuts per panel."	C
	15. Panel height: "This factor may affect cycle time in two ways. First, for higher wall panels, all panel elements (e.g., stud) are heavier. Whether this factor affects or does not affect cycle time depends on each worker. Some workers may find it harder to lift and load longer elements while other workers may not be affected. Second, I should adjust the machine's width between panels of different heights. This task is not required when a batch of panels of equal height are framed sequentially. Moreover, before I can adjust the machine, I must be able to push the completed panel downstream which means that the downstream station must be available. This task adds additional time to the cycle time for certain panels."	√
	16. Panel thickness: "A thicker panel is composed of thicker elements (e.g., 2×6 studs versus 2×4 studs). First, thicker elements are heavier and may be more difficult to lift and load. Second, thicker elements require a larger number of nails."	√
	17. Availability of shop drawings: "Shop drawings are always made readily available before they are needed."	X
	18. Wall panel design complexity (It reflects the variety of framing tasks that the operator must complete for a wall panel): "Aside from the varying time required by each type of element (e.g., single stud versus door), having a panel composed of single studs only versus a panel with a mix of various elements does not affect cycle time as the same steps are followed to load each element and run the machine."	X
	19. Quality of shop drawings (i.e., dictates the frequency of errors + delay + rework time if any): "This factor has a high impact on cycle time. The framing machine cannot read drawings with errors. As a result, I have to stop the work, inform the drafter, and wait for the revised draft before work can be resumed."	√
Worker	**20. Work shift (i.e., morning vs. afternoon) (which could relate to fatigue)**: "This may have an effect, but it depends on each worker and the workstation. For instance, younger workers may work faster at the beginning of the day and start slowing down throughout the day. Meanwhile, older workers may be more consistent in their speed throughout the day. Moreover, when the workstation is semi-automated, the worker's pace may be dictated by the machine's pace, which increases consistency. Sometimes, however, random events may happen throughout the day, and workers could become mentally drained in the afternoon."	√
	21. The day of the week (which could relate to work motivation or fatigue accumulation): "Monday mornings may be less productive as workers return from weekends, which may involve disrupted sleep schedules, alcohol, etc. Tuesdays are more productive as workers become dialled in. Thursdays (given that the company has a four-day work week) may be also productive because workers are motivated to finish their work earlier and start their weekend. Regarding fatigue accumulation, this factor may be more critical in the summer as workers get tired more quickly in higher temperatures and may get less rest after work. This means that their bodies may recover less between workdays, which may lead to fatigue accumulation."	√
	(Note: the operator's comment on this factor was generic and is not applicable to the case workstation given the operator's long years of experience.	X

	22. Learning curve: "This factor has a high impact on cycle time, but it varies among workers. Some workers are fast learners and retain knowledge, while others constantly seek help from others, thereby increasing cycle times."	
Machine	**23. Breakdowns**: "Some breakdowns result in complete work stoppages while others may only cause minor interruptions. For instance, the nail gun may occasionally shoot double nails, requiring extra work to cut the defective nails each time it occurs. Although this extends the framing process, it does not entirely halt production. These issues may occur approximately once every two weeks. In contrast, machine failures that require complete shutdown may last anywhere from 15 minutes to an entire day, and may occur approximately once every six months.	√
	24. Errors: "The machine may result in errors (e.g., nailing defect); a couple of minutes may be spared per incident."	√
	25. Nail gun refills: "The machine's nail gun was replaced with a new one of a different brand, but the new one must be refilled more frequently. Nail refills add more time to the cycle time for certain panels."	√
	26. Motion speed: "The machine has a constant motion speed."	X
Material	**27. Material type**: "Different types of materials (e.g., Laminated strand lumber (LSL) versus Spruce wood) vary in weight (e.g., LSL is heavier than Spruce), and heavier elements may be more difficult to lift and load."	√
	28. Delays in raw material supply: "There are no delays related to raw material supply."	X
	29. Delays in material preparation activities (e.g., sub-assembling door openings): "Material preparation activities are completed one shift or half a shift before the material is needed."	X
Workstation setup	**30. Distance between material inventory location and installation location**: "I must reach the nail inventory location every time a nail gun refill is needed, but this factor is correlated with the "nail gun refills" factor. All the other materials are reachable from my work location."	C/X
	31. Distance between tools location and workstation: "All the tools are located in a way that I can reach them without travelling."	X
Production line	(Note: the framing workstation is the first workstation on the wall production line) **32. Delay at downstream workstations**: "While waiting for the downstream workstation, I could start setting up the machine for the following panel instead of standing idle."	√
Factory operations	**33. Workload – Sq. Ft. per day**: "If the workload is low, the workers may become slower. Meanwhile, high workload may have two outcomes depending on the worker; while some workers may become faster trying to finish the scheduled work during working hours, other workers may become overwhelmed with the increased workload which, in turn, adversely affect their productivity."	√
	34. Overtime shift: "It depends on each worker. My speed during overtime shifts and regular shifts is consistent if overtime shifts are occasional."	X
	35. Weekly cumulative overtime: "In case of multiple overtime shifts during a week, workers do not have enough time to recover and become less productive."	√
External factors	**36. Ambient temperature**: "When the temperature exceeds 20 °C, workers get tired more quickly and become slower since there is no air conditioning in the factory."	√

Following this approach, the modeller will have a set of factors that are highly likely to influence cycle time at a given workstation (highlighted in green), another set of factors that are likely to influence cycle time (highlighted in orange and yellow), and a third set of factors that show minimal or zero likelihood of influencing cycle time (highlighted in red). The modeller will also have a good understanding of how these factors could influence cycle time and, hence, will be better positioned to rationally interpret the performance and the results of a machine-learning model developed to predict cycle times at the workstation under study. This facilitates the development of prediction models that more accurately capture the complexity of the process under study. It is important to note that not all influencing factors will become part of the prediction model. Some factors may be excluded due to various reasons such as data unavailability, an insufficient sample size, or weak correlations with cycle time compared to other factors. The modeller will nevertheless have an awareness of the potential effect of the excluded factors on the results. To further demonstrate the importance of following such a systematic approach for identifying influencing factors, let us consider a brief overview of the results obtained for building a model that predicts processing times (excluding delay times) at the case framing workstation. A multi-layer feedforward artificial neural network model was trained and cross-validated (using a 10-fold cross-validation) using data collected on 172 wall panels framed at the case framing workstation. The case company estimates the capacity of the workstation in linear meter per minute (m/min), so only panel length was used as a predictor variable in the first model. Based on cross-validation results, the mean absolute error was found to be 2.18 min. Adding the geometric properties of the given panel (i.e., Factors 1–16 in Table 1) reduced the error to 1.94 min, resulting in an 11% reduction in the error. Moreover, considering the complexity, day, shift, temperature, height difference, framing sequence, and date factors further reduced the error to 1.80 min, resulting in a total error reduction of 17%. The details of this neural network model are not presented in this paper due to space limitations, but will be presented in a future paper. Nevertheless, this brief overview of the results serves to highlight the value of dedicating time and effort to identifying and understanding the factors that influence process cycle time; Having a comprehensive pool of influencing factors is vital for the development of more accurate prediction models. As such, following the same approach for identifying influencing factors and building prediction models for different workstations, the modeller gains a deeper understanding of what factors drive cycle time variability and becomes well positioned to analyse cycle times across workstations. This, in turn, can facilitate workload balancing across workstations to ensure leaner operations.

CONCLUSIONS

This paper presented a structured approach for identifying and understanding the factors influencing cycle times at workstations in offsite construction factories, an essential step toward more accurate analysis of cycle times across workstations for the purpose of balancing production lines. The application of the approach was demonstrated in reference to a semi-automated, wood-wall framing workstation in a panelised manufacturing factory in Edmonton, Alberta, Canada. A total of 36 potential factors categorised into eight classes were identified based on observation, a cross-functional diagram of the process, and a literature review. These factors were further investigated based on the input of the workstation operator solicited in a semi-structured interview, and the factors were further discussed in light of the interview results. A brief demonstration of their effect on the performance of an artificial neural network model was presented, where using more factors as prediction variables in the model reduced the mean absolute error by 17%. A detailed description of the neural network model will be presented in a future paper. In short, this study demonstrated the value of expending effort on the identification and understanding of the factors influencing cycle times at workstations in offsite construction. Doing so can be expected to aid in streamlining and improving the accuracy of cycle time analysis for the purpose of applying Heijunka and balancing production lines, thereby minimising instances in which workers find themselves playing the role of the “hare”.

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EXPLORING OFFSITE CONSTRUCTION FOR THE CONSTRUCTION SECTOR: A LITERATURE REVIEW

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ABSTRACT

The construction sector is one of the largest producers of Gross Domestic Product globally and yet has shown little innovation in the last 20 years. Offsite has been touted as cheaper, faster, higher in quality and more environmentally friendly than onsite construction. The purpose of this paper is to review the current research into offsite construction and determine the barriers to adoption and benefits facing offsite construction. A systematic literature review was undertaken to gather relevant knowledge surrounding the subject matter using a database search of Scopus. It was found that knowledge was the largest barrier to adoption and that transcended multiple stakeholders, from the selection of the appropriate delivery methodology, how to design for optimized fabrication and finally how to interface with the onsite requirements. The benefits are a higher build quality, shorter project duration as both site work and fabrication occur at the same time, improved safety, and less material wastage. The Barriers come from design freezes earlier in the process and inflexible design for customization later in the build.

KEYWORDS

Off-site construction, modular construction, prefabrication, advantages, disadvantages

INTRODUCTION

According to McKinsey report (2020), the construction industry globally represents about $10 trillion annually making the construction industry the largest sector globally accounting for 13% of the worlds spending. The construction sector has demonstrated an average growth of 1% year over year compared to 2.8% growth of the global economy. McKinsey estimates the productivity performance in the construction sector represents $1.6 trillion in potential value added that could be generated by higher productivity. At the same time, the sector has suffered from inefficiencies and persistently low levels of productivity, largely the result of a fragmented supply chain, which still hampers its ability to embrace innovation (Department of Business Innovations and Skills 2013). When looking historically over the construction sector performance has shown a consistent 1% growth over the last 20 years (Mckinsey, 2020). The risks in the delivery of construction projects remain high, it is very typical for projects to run over schedule (typically 20% over) and costs (up to 80% over). When combining the high-risk

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factor with a low profitability, around 5% and that can be less depending on where in the value chain the specific construction company performs, construction companies are frequently the highest hit about insolvency (Mckinsey, 2020).

Based on the low growth and lack of efficiency, the construction industry is open to the risk of disrupters looking to capitalize on the $265m profit pool on the table. That profit pool could be further improved if projects can successfully shed risks. Industrialization in the (1970-1980), globalization (1990 -2000) and digitalization (2010-present) have all been key drivers of change in all other industries. As these drivers hit the construction industry, and are continuing to play a role, it is expected that disruption is likely within this sector (Mckinsey, 2020).

One solution that follows the key drivers to change and presents an opportunity for disruption within the construction sector, is the adoption of offsite construction (Mckinsey, 2020). Goddier and Gibb (2007) define offsite construction as the 'manufacture and pre-assembly of components, elements or modules before installation at their final location'. In a modern context prefabrication or offsite construction, which includes modular construction, refers to the pre-fabrication or fabrication of individual units that are assembled on-site to construct the final building (Jang, Ahn and Rob, 2022) (Marte Gómez *et al,* 2021).

The Prefabrication industry has been under review by different bodies of research and concluded it is faster by 34% cheaper by 19% and a higher quality than conventional construction (Shahzad, Mbachu and Domingo, 2015). A recent study has pointed to offsite construction to improve project efficiency (Steinhardt *et al*, 2016). Industry literature produced by the Modular Building Institute (MBI) touts the benefits of site construction to be further reaching adding to the benefits to include improved worker safety, reduced wastage, and offsets labour shortages (MBI, 2021).

Lou and Guo (2020) found that offsite construction is a complicated system that has multiple stakeholders influenced by different drivers. Inefficacies in design, transportation, storage, manufacturing, building installation and onsite construction all negatively influence construction costs.

The global offsite industry generated $130.4 billion in 2020 with expectation of forecast growth to $235 billion by 2030. As a market share this value places offsite construction at 1.3% (Market wise). Globally the adoption rate varies by region. The market share is very similar within the UK, Australia and the US representing prefabrication as less than 5% of the elements for housing compared to 84% in Sweden, 15% in Japan and 20% in the Netherlands (Cerro, 2021). This is also supported by the Journals reviewed with nine of the twenty-six studies coming from the UK and nine from Australia compared to none from Sweden or the Netherlands indicating that studies into barriers for adoption are not warranted and the value proposition is well established.

Goddier and Gibb (2007) research focused on the construction industry in the UK in 2007, the rate of evolution albeit slow in the construction sector has moved on in the last 15 years it opens up the content to questions regarding relevance today. Cerro (2018) work is more recent and focuses on the United States citing an affordable housing challenge with a lagging supply of homes indicating that adoption rate of innovative practices is still lagging, furthermore Cerro (2018) points to learning from Sweden, Japan and the Netherlands based on adoption rate. Steinhardt *et al*, (2016) researched the structure of the industry and what type of businesses were successful missing the advantages and disadvantages to adoption. Shahzad, Mbachu and Domingo (2015) reviewed 66 completed projects to assess their performance in New Zealand, however, this work did not look at the barriers to adoption. Lou and Guo (2020) only focused on costs for projects in China.

Based on the potential for efficiency gains and risk reduction in an industry that carries such a large profitability this research aims to identify the existing benefits and barriers to offsite construction to help inform why the adoption rate is so low in some regions and not in others.

The construction market value is there and has remained very stable, which also begs the question why disruption is not more prevalent within this sector. Thus, this paper seeks to undertake a systematic review of current literature studies and further answer the following set of research questions:

RQ1. What is the current knowledge surrounding the barriers adoption of offsite construction?
RQ2. What is the current understanding of the benefits to offsite construction?

METHOD

Several types of literature review can be identified in the existing knowledge. According to Clark et al. (2021), narrative review and systematic review are the main types of literature review. When compared with narrative review, systematic review provides comprehensive and rigorous analysis of the existing knowledge on a selected topic (Tranfield et al., 2013). This research method has been used to analyse the existing knowledge on apprenticeship (Daniel et al., 2020) and public private partnership (Tang et al., 2010), among others. In the current research, the systematic review was done in three stages. The initial stage identified the key papers of interest based on a database search of Scopus. The second stage involved limiting relevant and excluding irrelevant information in the search criteria. The final stage was conducted by reviewing the content and analyzing for relevance against the research aims and objectives.

Based on the research questions, a list of key terms was identified for the literature search. The shortlisted terms were further analyzed to identify additional words commonly used in different geographic regions. For example, 'Offsite' is used in the UK as supposed to Malaysia where the use of "Industrialized" is more common. The initial search data set was used as a scoping study to identify other key words that may appear on additional studies that would be otherwise excluded from the search criteria.

The research team decided to remove conference papers due to limited online access. The journal papers included in the study's sample have been peer reviewed and this process validates the findings emerging from those studies. The benefit of secondary research is that the breadth of data available is very extensive compared to a limited primary research approach. By accessing Primary sources, the intent is to access the original research into the field and by focusing on peer reviewed journals the quality will be controlled. The roman emperor and philosopher, Marcus Aurelius had a similar thought when in 160 he said:

"Nothing has such power to broaden the mind as the ability to investigate systematically and truly all that comes under thy observation in life"

Scopus database was selected as it contains the largest abstract database of peer-reviewed literature. With multiple search criteria options it is very useful in identifying the key studies of focus as these primary sources of information are updated on a regular basis. A potential limitation of the study is the use of only Scopus as the research database and may miss some research studies as a result that are available on other databases. The thinking in only selecting Scopus was to limit study duplication and potential over complication of the research data by trying to work through multiple databases simultaneously. Google Scholar was rejected as it is not a database and would not allow for a systematic review of the available literature. The use if Google Scholar would require a labour-intensive manual approach that was rejected as the research method due to the time required and lack of repeatability. Web of science was rejected based on the initial number of studies returning 705 studies compared to 1,963 with Scopus. It was determined that Scopus cast a wider net initially therefore offering a larger research body as a basis.

("offsite construction" OR "off-site construction" OR "off site construction" OR "offsite Manufacturing" OR "off-site Manufacturing" OR "off site Manufacturing" OR "offsite Manufacture" OR "off-site Manufacture" OR "off site Manufacture" OR "offsite fabrication" OR "off-site fabrication" OR "off site fabrication" OR "Prefabrication" OR "Pre-fabrication "OR "Modern Methods of Construction" OR "Lean Construction" OR "Industrialized Buildings" OR "Modular Construction" OR "Modular Building") AND ("Barrier" Or "Benefit*"OR "Popular" OR "adoption")

The first stage generated a total of 1,963 potentially relevant studies based on the database search. After limiting the results to those available in English, Journal articles and duplicates a total of 238 studies were reviewed by subject area, title. This process was relatively simple to undertake and weeded out several irrelevant studies. For titles that were not as clear or abstracts that answered part of the research focus a more detailed review of the abstracts was required leaving 141 studies. Following the abstract review, a total of 69 studies were deemed to be potentially relevant and required a full text review including introduction, findings and conclusions.

Upon finalizing the screening process, the remaining research left 28 studies that required a full content analysis. Once confirmation against the research aims and objects were confirmed the list was finalized in SCOPUS to create a bibliography. Further data relating to country of origin, guiding themes contained within the literature for (1) benefits of offsite construction (2) Barriers to adoption.

RESULTS

Literature map on the Emerging Themes of Offsite Construction		
Benefits		**Barriers**
Higher quality		**Lack of knowledge of efficient delivery**
Tam et al 2006; Blismas, pasquire & Gibb 2007; Si et al. 2021; Goodier & Gibb 2007; Zhang, Skitmore, Peng. 2014; El-Abidi et al 2019: Li 2020; Goodier et al, 2019: Cerro. 2021		Popovic, Elgh & Heikkinen, 2021; Shahzad, Mbachu, Domingo. 2015: Mossman, Sarhan. 2021; Sutrisna, Goulding, 2019; Jabar et al, 2019: Goodier, 2019
Shorter schedule		**Higher Cost**
Tam et al 2006;Blismas, pasquire & Gibb 2007; Goodier & Gibb 2007; Si et al. 2021; Zhang, Skitmore, Peng. 2014; El-Abidi et al 2019; Shahzad, Mbachu, Domingo. 2015; Peltokorpi et al, 2018; Li 2020: Goodier et al, 2019: Cerro. 2021		Pan, Gibb & Dainty; 2007; Lou and Guo 2020; Blismas, pasquire & Gibb 2007; Goodier & Gibb 2007; Jang, Ahn, Roh. 2022
Reduced costs		**Social Perception**
Tam et al 2006; Saad et al. 2021; El-Abidi et al 2019; Shahzad, Mbachu, Domingo. 2015; Mossman, Sarhan. 2021: Cerro. 2021		Saad et al. 2021; Shahzad, Mbachu, Domingo. 2015
Waste reduction		**Different design process**

Tam et al 2006; Blismas, pasquire & Gibb 2007; Si et al. 2021; Loizou et al 2021: Cerro. 2021		Tam et al 2006; Pan, Gibb & Dainty; 2007; Zhang, Skitmore, Peng. 2014; Popovic, Elgh & Heikkinen, 2021
Health and safety		**Availability of multiskilled labour**
Blismas, pasquire & Gibb 2007; Zhang, Skitmore, Peng. 2014; El-Abidi et al 2019: Goodier et al, 2019		Goodier & Gibb 2007; Zhang, Skitmore, Peng. 2014; El-Abidi et al 2019; Arashpour et al 2014
		Complex supply chain
		Sooriyamudalige et al, 2020

Figure 1: Literature map on the Emerging Themes of Offsite Construction

The benefits and barriers to adoption from the systematic review have been placed to represent the common findings in the Literature Map as shown in Figure 1. There are contrasting views across the study, interestingly the researchers are more aligned on the benefits based on the tighter grouping and more succinct topics when compared with more sporadic points on the barriers to adoption.

RQ1. What is the current knowledge surrounding the barriers to adoption of offsite construction (globally)?

The biggest barriers to adoption are knowledge, higher cost, perception, design, lack of skilled labour and complexities in supply chain.

Knowledge on how to identify the risks of offsite construction and apply the learnings to meet the business objectives is required to increase the rate of adoption (Peltokorpi, 2017). The existing knowledge as it pertains to onsite delivery does not apply in the same way as the entire approach in project execution is different from design, fabrication, transportation, and site installation (Peltokorpi, 2017). Education specifically on the following areas: in first selecting the appropriate delivery methodology based on project goals, design suitable for manufacturing reducing turbulence, robust project execution planning with an understanding on risks mitigation strategies, integration of supply chain earlier in design to reduce the introduction of complexity and lastly procurement strategies to align with project objectives.

Pre-construction requires more upfront skilled labour in design due to the complexities that need to be solved earlier in the process than compared to onsite building (Navaratnam *et al,* 2019). This is partly driven by the requirement to order long led items earlier in the process and in part due to the design needing to be more complete earlier for design freezes to be in place prior to fabrication.

Supply chain integration focuses on the flow of materials from suppliers to the site on time for the work to commence and providing value across the interrelated business (Sooriyamudalige *et al*, 2020). In onsite construction this is a well-established process for mature general contractors. Offsite construction however follows a different network, in most cases, of unfamiliar supply chain suppliers in the form of skilled design practitioners, fabricators and installers (Sooriyamudalige *et al*, 2020). By a conventional site builder to integrate offsite construction it is fair to deduce an entirely new supply chain will be required to deliver the project. First, understanding of the complex supply chain is a barrier to adoption of offsite construction and secondarily the knowledge of how to plan and implement the delivery approach to avoid delays is lacking. Regionality has an impact on the research findings specifically in the complexities in the local supply chain, regulatory processes, and government incentives country to country (Sooriyamudalige *et al*, 2020; Zhang, Skitmore and Peng, 2014).

Tam *et al* (2017) found that inflexibility for change in design scored the highest challenge in their study and happened to be derived from previous project experience whereby the design was not frozen and doing so caused the consultant and client team frustration in unmet goals. Design happens earlier in the process for offsite construction and requires an early integration of stakeholders including manufacturers and suppliers all leading to a long lead into the construction process (Pan, Gibb and Dainty, 2007). Changes in design that happen later in the fabrication process can be more costly than conventional construction which may also be linked. Furthermore, understanding some of the barriers to adoption specifically around complex supply chains and lack of knowledge may also be driving costs up in some projects. Prefabrication is not new and with that comes preconceived ideas of how the building approach will influence the project outcomes based on past experiences and dated connotations from the post war reconstruction (Shahzad, 2015).

RQ2. What is the current understanding of the benefits to offsite construction?

The benefits to offsite construction, that are widely supported, include a reduction in schedule and higher quality. Additionally, a reduction in costs, wastage and improved safety round out the remaining findings.

Pre-fabricated buildings are constructed in controlled environments out of the weather conditions leading to a higher quality of build than compared to onsite construction (Shahzad, Mbachu and Domingo, 2015). Inside fabrication facilities technology can be deployed to increase the accuracy of material processing, reducing waste and improve built quality (Cerro, 2021). Due to the fragmented construction approach with buildings being constructed separately to the site allowing progression of both entities the progress at the same construction times can be reduced if both the manufacturing and the site maintains the as planned schedule (Si *et al,* 2021). Si *et al* (2021) goes on to identify a potential contracting strategy to help financially incentivize on time completion, in reality it would be very hard to integrate a new contracting method that is not normalised in the industry.

Shahzad, Mbachu and Domingo (2015) connotes a reduction in cost and schedule savings with conventional construction taking longer than offsite therefore indicating a lower cost for prefabricated buildings. The softer benefits of health and safety appear to be less relevant as a primary driver for winning work based on how larger contracts are awarded and tendered. Safety is perceived as a baseline opposed to a tangible differentiator like faster completion or lower cost.

DISCUSSION

Pan *et al* (2007) interviewed the top 100 performing home builders in the UK and found the majority of stakeholders are satisfied with traditional construction methods and furthermore the drivers for building methodology are tied to the historic considerations for contractors. When considering if a construction scheme will proceed with traditional onsite or prefabrication methods contractors typically make decisions based on schedule, cost, quality, and productivity. Pan *et al* (2007) study did not differentiate between actual stakeholder experiences or if the responses were based on perception. The drivers for decision making are important in understanding which of the benefits, and barriers are most relevant to the broader industry to determine if the barrier is a result of an actual route cause issue that needs to be solved or based on a preconceived perception because the remedies are different for each outcome.

BENEFITS

Schedule efficiencies are gained due to the fragmented delivery whereby the site progresses in the same sequence as conventional methods and the offsite components are manufactured at a factory simultaneously before being put together at site (Arashpour *et al*, 2014). This can result in schedule efficiency over that of site-built projects due to a reduction in time onsite with up to 34% in time savings (Shahzad, Mbachu and Domingo, 2015). ***Shorter schedule*** is thought to be the largest benefit of prefabrication compared with traditional construction (Tuesta *et al,* 2022), this point is supported by nine of the thirteen contractors surveyed by Goodier and Gibb (2007) in their contribution *The research into the future opportunities for offsite in the UK.* Goodier Gibb (2007) used their previous studies in the literature review, this could have led to bias in towards the findings of this later research being influenced by outdated findings and missing current thinking. The incorporation of prOSP (pre curser to Buildoffsite) would help answer the question as to the future opportunity of prefabrication in the UK construction industry but is unlikely to offer a balanced view due to the pro-offsite nature of the body. The inclusion of a sub section of stakeholders including clients, construction industry, offsite fabricators lend to a triangulation of opinions on the same perceived benefit adding further credibility to the results.

Offsite construction is bound by the same building codes as onsite construction and uses the same certified design professionals in the process. As such assembled buildings are virtually indistinguishable from their on-site counterparts (Chen *et al*, 2019). On site construction by contrast can experience variable environments with inclement weather conditions challenges with quality forcing rework and labour constraints for specialist trades (Arashpour *et al*, 2014). Due to offsite buildings being constructed in a factory setting, where the conditions are controlled and the skilled work force is performing repeatable tasks, a consistent and **higher quality** of fabrication can be produced (Jang, Ahn and Roh, 2022). None of the research challenged the quality of the offsite process therefore it may be surmised the body of knowledge agrees that quality is better when factory produced.

Extensive research has been conducted into the **cost impact** of offsite delivery to project budgets. It is reported to reduce costs derived from shorter schedule and more efficient use of labour. However, there can be an increase in material costs, for example the doubling up of interior walls in volumetric deliveries or shipping walls that are then disposed of once the components reach the site. It is expected that even with the increase in material for building completion the cost is offset against material wastage from onsite building due to inclement weather and mistakes. For the cost benefit to be realized the labour on the project needs to be managed effectively and any impacts of material costs to be reduced (Loizou *et al.* 2021).

It is important to recognize the delivered cost of a project not just the initial price since prefabrication can deliver a higher quality with less wastage and a significant reduction in snags or defects at the close out stage offering a potential lower end cost (Goodier and Gibb, 2006). Modular construction costs in Singapore are reported to be higher than site built concrete construction as much as increase of 8.1% (Jang, Ahn and Roh, 2022), however only one direct comparison was used as a comparison with a steel delivery. If a more robust process was used to evaluate the multiple solutions, there may have been a potentially different outcome for example that case study used would have likely been delivered through wood framing in North America.

Offsite construction, no matter which form, requires a different design approach than compared with traditional methods. The more complex the project and delivery methodology chosen has a direct correlation to the amount of specialized knowledge experts, sub consultants and inextricably the time it takes in predesign **increasing costs** (Navaratnam *et al,* 2019). Largely these costs can be offset by the time savings when moving into production and a shorter duration of occupancy.

The **environmental** benefits of not using wet construction methods in some forms of prefabrication prove beneficial in diverting waste from land fill. (Cerro, 2021). Global construction activities produce approximately 25% of all solid waste, with 40% of material in landfills as a result of construction activities. (Loizou *et al,* 2021). To fully understand the environmental benefits of modular, more recent studies have elected to review the full life cycle assessment (LCA) to better determine the impact (Jang, Ahn and Roh, 2022). Life Cycle assessments when using conventional process do not reduce the margin of error to an acceptable level in part due to the complexity and diversity of the supply chain (Aye *et al*, 2012). This has led to an absence of detailed research in environmental performance to substantiate the environmental benefits as it pertains to prefabrication.

Social sustainability covers the wellbeing people get from the places in which they reside and work. Recent research indicated the offsite construction is a **less hazardous environment** and is more controllable with a reduction in injuries and less onsite noise (Loizou *et al,* 2021). The fabrication process can be louder, but this is often in industrial estates having a lower impact on the community. Li *et al* (2010) argues that due to the size of prefabricated components the risk profile on sites can increase creating a more hazardous environment to work in but does not provide evidence to support or a methodology for the research conducted and does not consider the vertical integration of trades in the precast industry like Steinhardt *et al*. (2019). Due to less time onsite prefabrication reportedly has less safety risks by default. (Blismas, Pasquire and Gibb, 2007; Zhang, Skitmore and Peng, 2014; El-Abidi *et al*, 2019; Goodier *et al*, 2019).

BARRIERS

Tam (2007) found that **inflexibility for change in design** scored the highest challenge and happened to be derived from previous project experience whereby the design was not frozen and doing so caused the consultant and client teams frustration in unmet goals (Tam *et al*, 2007). The research method in this case included a survey based on a literature review to identify the key areas to be graded as benefits and barriers. The author covered a broad base of stakeholders but did not disclose how many of the respondents were represented in the study results making it challenging to assess the validity of the results.

Design happens earlier in the process for offsite construction and requires an early integration of stakeholders including manufacturers and suppliers all leading to a **long lead** into the construction process. (Pan, Gibb, and Dainty, 2007).

A significant choking point in the delivery of offsite construction in China is related to the inefficiency of **Supply chain**. The trades are complex and disjoined in their approach leaving coordination to be challenging. Unlike more developed countries with mature supply chain and standardized construction programs (Zhang, Skitmore and Peng, 2014). Compared to the UK where there is a standardized building system, by comparison, the supply chain limitations inhibit the design community adoption of offsite construction. (Pan, Gibb and Dainty, 2007).

Aside from the benefits associated with offsite construction, the industry is still dogged by some of the same challenges as onsite construction, in terms of inefficient prefabrication methodologies. These inefficiencies are caused by dispersed and often **lack the coordination** to prevent work starvation (Arashpour *et al,* 2014). Most factories are set up in a linear fashion whereby each station is trained to perform one task. When inefficiency is found a bottle neck can be created when oversubscribed tasks take longer to perform than others. The more efficient a building can be constructed in a factory setting the better the flow and less turbulence it generates. Construction by nature contains a high degree of turbulence. The degree to which the prefabrication encounters **turbulence** due to the variation in dimensions, material selections, transportation requirements can degrade the fabrication system (Mossman and Sarhan, 2021).

Offsite construction uses a different supply chain and requires in-depth understanding by **skilled labour** of how the buildings are designed, built, moved and interface with the site. There are a limited number of professionals with this skill set today (Sooriyamudalige *et al*, 2020).

Si *et al* (2021) suggests that the challenges faced with **inefficient communication** caused by a fragmented delivery process whereby work and onsite are controlled differently can be resolved by realigning the contract terms whereby if the factory causes a delay they are penalized and where the General contractor allows a production schedule that favors the factory, they are incentivized. This appears to be a complicated solution that most stakeholders will not be familiar with. Where there is a stakeholder lack of understanding this approach may lead to further complications as it doesn't align with traditional construction procurement practices (Daniel *et al,* 2018).

Perception within the market has a negative impact on the adoption rate whereby past experiences have not been positive or concerns with quality from industry examples in past eras influence decision of today. The lack of flexibility in the design, typically being limited to the builders pre-determined designs (Shahzad, Mbachu and Domingo, 2015) contributes to the decision of conventional builds.

Knowledge Typically Suppliers (30%) believe their customers are not fully educated on the benefits and barriers for offsite construction compared with the designs (73%) and Builders (54%) who believe they are fully aware (Goodier and Gibb, 2007). Traditional construction experience and understanding how the offsite approach of choice works is a knowledge gap that needs to be closed to have a better adoption rate of prefabricated construction (Goodier and Gibb, 2007).

Summary

Global perspectives help to inform the potential benefits and barriers to adoption. The local supply chain, government involvement, knowledge and perceptions all have an impact on the potential outcomes of the project success with an offsite delivery. A gap in the research is: *What knowledge is required effectively to deliver offsite construction in Canada leading to more desirable outcomes?*

CONCLUSION

This research sets out to identify the benefits, and barriers to adoption for offsite construction.

Based on the qualitative analysis of this study it can be concluded that efficiency can be improved when the benefits of higher quality and improved schedule are realized when compared to conventional construction. The barriers are largely around design and understanding of how to work within an offsite delivery process whereby design is frozen earlier. When the design is not efficient for the fabricator it impacts the project line flow and has a knock-on impact to cost and schedule. This research found a lack of knowledge, specifically in design for manufacturing, interfacing between onsite and offsite works, understanding the supply chain and how to mitigate the complexities create further barriers to adoption.

The results of this research provide relevant industry stakeholders with the identification of benefits, and barriers to adoption of offsite construction. By understanding the barriers adoptees can effectively plan mitigation strategies to avoid issues with design freezes and potential cost increases. Recognizing the barriers to adoption will inform potential objections from partners that may need to be overcome to progress with an offsite delivery and help to inform new supply chain strategies.

This study was limited to using Scopus database only, as such the use of more databases could have provided richer evidence.

The findings confirm that there is a gap of knowledge in Canada, to better understand the implication from the results a future study could answer questions of; stakeholder knowledge, how to interface effectively between the fabrication and onsite works and what influence the local supply chain complexities have upon the delivery methodology. Based on this evidence it is recommended that an empirical study be conducted in the specific geographical region of Canada to capture the intricacies of local supply chain based on the limited research into this region specifically to interrogate the findings locally. By using a cross section of the industry including design consultants, fabricators, contractors, and customers would better allow to differentiate between lived experience and perception in the study and focus on the knowledge gaps that exist to better provide specific solutions.

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BENEFITS OF ROBOTIC UTILIZATION IN THE PREFABRICATED CONSTRUCTION INDUSTRY

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ABSTRACT

Electronically automated machines with a longer lifespan than human work make up robotic technology. The aging workforce in the prefabricated building business may be addressed by robots, which explains why there are less young people employed there than in other sectors of the economy. Robotic technology is cost-effective since it reduces the time required to complete building projects and the expense of manpower, which also lessens the possibility of accidents. Therefore, it is crucial to consider the benefits of robotic technology adoption in the context of the South African prefabricated building industry. The study adopted a quantitative survey method to obtain data from architects, civil engineers, quantity surveyors, mechanical and electrical engineers, construction managers, and project managers. The data were examined using SPSS, and the suitable dispersion measure and inferential statistics were used. According to the report, the key benefits of adopting robotic technology in the prefabricated building business in South Africa include faster construction timeframes, improved work quality, and increased productivity, efficiency, and profitability. The results also showed that improving worker health and safety would result from introducing robotic technology to the prefabricated building industry. The study's conclusions suggest that because of the advantages discovered, the prefabricated building industry in South Africa should adopt robots more swiftly.

KEYWORDS

Robotics, Prefabrication, Accuracy, Construction Duration

INTRODUCTION

Mhlanga & Moloi, (2020) claim that South Africa is one of the world's emerging nations. Because building processes have changed and improved through time, the industry is currently experiencing a productivity issue due to a lack of investment in technical development. The South African construction industry must adapt to technological advancements on a worldwide scale since technology is essential to increasing effectiveness. According to Akinradewo et al., (2021) the use of robotic technology in the prefabricated building sector would improve worker health and safety since robots will do laborious activities on the construction site. Also, Maurice et al., (2018) opined that there will be lesser health problems associated with physically demanding construction labor. Its adoption is primarily for employee welfare. Less

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accidents and unplanned events will occur because of the use of robot technology in the prefabricated construction sector. Prefabricated materials might endanger the health and safety of manual employees since they are bulky and heavy. In modern businesses like the chemical and educational industries, robots have helped lift the heavy goods (Grau et al., 2020). According to Adekunle et al., (2022), robotic technology will also handle the repetitive jobs, cutting down on task length. Consequently, projects will be finished on time and within the allotted time framse without experiencing any more delays. It is crucial to consider the advantages of robotic technology in the context of the prefabricated building sector.

Robotic technology is the automation of machines using electronics to improve their accuracy (Toma et al., 2022). They outlive human effort in terms of lifespan. Robots are the answer to the labor shortfall caused by the construction industry's needs and an aging labor force (Flandorfer, 2012). Since these robots are trained to carry out certain jobs in detail, their precision minimizes errors brought on by improper handling and underestimation of building processes. Therefore, using robot's technology improves the quality of the job produced. Robotic technology can save money since it cuts down on labor expenses and building time. There seems to be a lack of information in the literature about the advantages of using robotics within the prefabricated construction industry practices being carried out in developing and sub-Saharan countries like South Africa, aside from the issue of the prefabricated construction industry's poor adoption of digitization. It is crucial to keep in mind that South Africa is only now beginning to adapt and use prefabricated construction. This study evaluated the benefits of adopting robotic technology for prefabricated construction processes within the South African construction industry based on this information, with the goal of suggesting potential actions that would lead to an increase in utilization.

LITERATURE REVIEW

Due to a number of well-known obstacles, the adoption of robotic technology within the construction sector has historically been met with great opposition (Carra et al., 2018). Thanks to several recently discovered forces that are driving innovation processes within the construction sector, the situation is now changing quickly. Additionally, these factors gave rise to several easily visible trends that are altering how buildings are designed, constructed, and maintained. Because there is less human labor present when robotic technology is deployed, there are less opportunities for mishaps and strike breakouts (Delgado et al., 2019). As a result, robotic technology is a more dependable alternative to manual labor in terms of efficiency, production, and profitability. It is crucial to understand that prefabricated components are made in a factory with rigorous regulations, in a regulated, and under constant observation environment. This suggests that enhanced work supervision and factory inspections are carried out to guarantee that the components adhere to specification, according to Zhu et al., (2021). Additionally, components are produced in factories and merely transported to the construction site to be built into the required structure, requiring less handling and storage of resources. As building projects are delivered in modules to be built on site, less material storage and handling leads in lower site waste (Mahbub, 2012). The factories are constructed so they may repurpose building materials that were utilized in a prior manufacturing or production process. Due to this phenomena, more recycled materials are being used (Bademosi & Issa, 2022). Prefabricated construction is an ecologically beneficial method of building that will aid the sector in attaining its aims for sustainable growth. Robotic technology can help with material logistics and on-site assembly for reasons of health and safety.

Since the construction sector is dangerous to work in, businesses aim to adopt safer practices. And as a result of human's construct subassemblies in climate-controlled factories, there is a reduced likelihood of issues with dirt, dampness, and other environmental dangers when employing robotics for prefabrication (Malomane & Musonda, 2022). Prefabricated building structures and assemblies are now as sturdy as conventional structures because to advances in engineering and prefabricated material technology. A factory-controlled environment offers greater safety compared to a project job site since employees and potential tenants are more vulnerable to weather-related health concerns on construction sites. Additionally, stricter production protocols and practices shield employees from workplace accidents. Despite the importance placed on worker safety at construction sites, shifting ground conditions, weather-related circumstances, and wind all increase the risk of accident. Another advantage is that the building business will become more productive, efficient, and profitable as a consequence of the implementation of robotic technology in the prefabricated construction sector (Tankova & Da Silva, 2020). Given how few construction companies now use automation, robots hold enormous potential for revolutionizing the sector.

Robotic technology's use in the lifting of large objects will reduce the demand for physical labor because workers won't need to engage in arduous activities there (Kyjanek et al., 2019). For the safety of human workers as well as the financial health of heavy industrial and construction enterprises, a robot is an attractive alternative to a human employee. The world population is aging, and the construction sector will have a difficult time attracting new employees in the future. The use of robotics technology appears to be the industry's panacea. Companies will recruit younger, more technologically knowledgeable employees if they are regarded to be implementing cutting-edge techniques and technology (Oke et al., 2019). Additionally, this will guarantee that businesses can retain productivity when the number of people in the globe who are working-age declines. Prefabricated materials are produced in facilities with extensive quality assurance and control procedures (Yahya et al., 2019). Realizing the harmony and unity of all parts is essential to building quality management. Considering construction quality management in its whole will help to advance the development of construction quality. Robotics adoption not only enhances quality management through the creation of economic advantages, but also fosters the growth of businesses (Adekunle et al., 2022). Less accidents and unplanned events on the job site will come from the application of robotic technology in the building procedures. Since robots are machines and are programmed to do certain tasks, there are fewer opportunities for error than there are with manual labor.

Robotic technology is appropriate for heavy lifting in a construction setting where flexibility and range are crucial (Pan et al., 2018). Robotic technology lowers building expenses and ultimately generates enormous profits for construction companies because it removes the possibility of human mistake and waste while producing results that are extremely exact. The robots have a long-life span because they are machines they merely need to be maintained and updated as frequently as necessary (Pan & Pan, 2019). Literature demonstrates that employees may easily disassemble and move sub-assemblies to other locations (Huang et al., 2022). But since prefabricated building technologies offer flexibility without stifling innovation, general contractors and clients are increasingly turning to alternatives. The use of robots in prefabricated and modular building opens up a world of possibilities by allowing for flexible structural design.

METHODOLOGY

This study used a structured questionnaire that was given to quantity surveyors, architects, engineers, construction managers, and project managers as part of a quantitative methodology. These experts were chosen from the public and private (contractor and consulting) sectors. These experts were chosen from the public and corporate sectors of Gauteng, the country's largest province. The province was chosen due to its strategic position and capacity to handle administrative duties. The province is also the core of high-end service delivery for industries including manufacturing, technical and industrial services, and construction. Those registered with the different professional organisations in South Africa and other countries in the Southern African area were the construction industry's target professions. This precaution was deemed essential for the poll to guarantee that the findings accurately reflected the public's perception of the advantages of adopting robotic technology. 110 professionals were chosen as the sample size using a non-random sampling approach. As in the study conducted by Adekunle et al., (2022), a closed-end questionnaire was created and split into two portions. The purpose of the first portion was to gather demographic data from the respondents, such as their level of education, occupation, and experience. The purpose of the second section was to evaluate the benefits of using robots. In order to evaluate the advantages of robotic use, a 5-point Likert scale was used. 88 of the 110 questionnaires that were distributed received a response, which is an 80% response rate. When analyzing the collected data, percentages were used to evaluate the advantages of using robotic technology in pre-fabricated homes, and Mean Item Score (MIS) was used to rate the data on the respondents' backgrounds. Kruskal-Wallis was also used to compare respondents' perspectives based on their years of experience. The Cronbach's alpha reliability test, which was used to evaluate the data sets' dependability, yielded a result of 0.905, which denotes a high degree of consistency.

FINDINGS AND DISCUSSION

In terms of gender, the statistics showed that men, who made up 73.2% of respondents, received more responses than women, who made up 26.8% of respondents. In terms of profession, 14.2% of respondents were civil engineers, 13.3% were mechanical and electrical engineers, 24.5% were quantity surveyors, 4.5% were project managers for construction, 15% were managers of construction, and 13.2% were project managers. Moreover, 49.4% of respondents worked for contracting firms, while 29.9% were consultants. Also, 20.8% of them worked for the government. In addition, more than 87% of the respondents claimed that they had worked on seven or more projects, while the remaining 13% had only worked on six or less. The responses were trustworthy and credible as, on average, more than 90% of respondents had over five years of working experience in the South African construction business, which is a significantly high proportion.

Table 1 shows the respondents ranking of the benefits of the application of robotic technology in the South African prefabricated construction industry in Gauteng. The results reveal that ‘shortens construction duration’ was ranked first with a mean score of 4.25 and standard deviation of 0.821, ‘Improved quality of work’ ranked second with a mean score of 4.24 and standard deviation of 0.951, ‘productivity, efficiency and profitability’ ranked third with a mean score of 4.22 and standard deviation of 0.856, ‘less material storage and handling’ ranked fourth with the mean score of 4.16 and standard deviation of 0.857, ‘less accidents and unforeseen circumstances’ ranked fifth with the mean score of 4.14 and standard deviation of 0.939. Furthermore ‘suitable for lifting heavy materials’ ranked sixth with the mean score of 4.10 and standard deviation of 0.900, ‘improved work supervision’ ranked seventh with the mean score of 4.04 and standard deviation of 1.095, ‘improved health and safety culture’ ranked eighth with the mean score of 4.02 and a standard deviation of 1.104, ‘Reduced mishandling and miscalculation’ ranked ninth with the mean score of 4.00 and standard deviation of 0.980, ‘reduce health issues for strenuous activities’ ranked tenth with the mean score of 4.00 and a standard deviation of 1.077, ‘reduced site waste’ ranked fourteenth with the mean score of 3.88 and standard deviation of 0.931, ‘long-life span’ ranked eleventh with both having the mean score of 3.88 and standard deviation of 0.952, ‘increased use of recycled materials’ ranked thirteenth with the mean score of 3.86 and standard deviation of 1.020, ‘solves ageing population crisis’ ranked fourteenth with the mean score of 3.71 and standard deviation of 1.119 and ‘cost effective’ ranked fifteenth with the mean score of 3.45 and the standard deviation of 1.006 as the least benefit of the application of robotic technology in the South African prefabricated construction industry.

Table 1: Benefits of Adopting Robotic Technology

Benefits	Rank	Mean	Std. Deviation
Shortens construction duration	1	4.25	0.821
Improved quality of work	2	4.24	0.951
Productivity, efficiency and profitability	3	4.22	0.856
Less material storage and handling	4	4.16	0.857
Less accidents and unforeseen circumstances	5	4.14	0.939
Suitable for lifting heavy materials	6	4.10	0.900
Improved work supervision	7	4.04	1.095
Improved health and safety culture	8	4.02	1.104
Reduced mishandling and miscalculation	9	4.00	0.980
Reduction of strenuous activities	10	4.00	1.077
Reduces site waste	11	3.88	0.931
Long-life span	12	3.88	0.952
Increase use of recycled materials	13	3.86	1.020
Solves ageing population crisis	14	3.71	1.119
Cost effective	15	3.45	1.006

Table 2: Kruskal-Wallis Test Showing P-Values for Measures

Benefits	P-Values
Shortens construction duration	0.003
Improved quality of work	0.000
Productivity, efficiency and profitability	0.000
Less material storage and handling	0.064
Less accidents and unforeseen circumstances	0.827
Suitable for lifting heavy materials	0.000
Improved work supervision	0.000
Improved health and safety culture	0.004
Reduced mishandling and miscalculation	0.013
Reduction of strenuous activities	0.000
Reduces site waste	0.002
Long-life span	0.000
Increase use of recycled materials	0.044
Solves ageing population crisis	0.031
Cost effective	0.022

The results of this study back up Delgado et al., (2019) claim that the South African prefabricated building sector may reduce construction time by using robotic technology. As a consequence, projects will be finished on time and within the allotted time frame without experiencing any more delays. This advantage received the highest ranking, indicating that respondents believe it to be the most significant benefit that will hasten the adoption of robotic technology in the prefabricated building sector. Additionally, the study supported Chea et al., (2020) who claimed that using technology improves the caliber of work produced. Robotic technology is a more dependable alternative to manual labor since it will increase efficiency, production, and profitability in the prefabricated building business. Application of robotic technology leads in less material storage and handling since materials are created at the plant and only delivered to the site to be built to the appropriate structure because they are prefabricated components. This is in line with the findings of a research by (Bademosi & Issa, 2022), which predicted that the use of robot technology will lead to fewer mishaps and unanticipated events. The results of this study further confirm Oke et al., (2019) assertion that robots will be useful for carrying large goods on site, especially prefabricated pieces. Prefabricated parts are created at a plant that adheres to stringent regulations and is closely watched. This will lead to better job supervision because factory checks are done to guarantee that the components meet specifications. According to Akinradewo et al., (2021), the use of robotic technology in the prefabricated building sector would improve worker health and safety since the robots will handle activities that are riskier.

Robots are machines whose accuracy prevents errors caused by carelessness and error in calculation, depending on their capacity and what they are programmed to do (Pan et al., 2018). However, the respondents to this study gave a low rating to this benefit, believing that it does little to encourage the use of robotic technology. Robotic technology will thereby lessen the health problems caused by physically demanding construction labor since its adoption will improve employee wellness. In line with Kumar et al., (2016) study, the outcome also showed that less material handling and storage leads to less waste generated on the site. Prefabricated buildings require no adjustments, so materials are delivered on site and put together to create the desired structure. Despite the fact that robotic technology has a longer lifespan than human labor (Pradhananga et al., 2021), the results of this study do not appear to view this advantage as a key driver for the use of robotic technology in the prefabricated construction sector. According to the study's findings, the fact that factories are built so they may reuse materials from earlier production processes does not significantly influence whether or not robotic technology will be applied there. This also increases the usage of recyclable materials. The findings of this study do not support Aghimien et al., (2020), who claimed that robots are the answer to the construction industry's ageing population, which results in fewer young people than in other industries. Even though this is a benefit, it does little to influence the construction industry's adoption of robotic technology in the prefabricated construction sector.

The cost effectiveness of robotic technology was the benefit that received the lowest ranking in this study for its use in the prefabricated building sector of South Africa. Robotic technology, according to Chen et al., (2022), is cost-effective since it lowers labor expenses and construction time, which has a cost associated with it because construction equipment must be hired; the less time spent on a project, the more money is saved. Because they are not considering the fact that robotic technology shortens the period of building, which would save money, the respondents to this survey do not see the benefit as being crucial to encourage its implementation.

A Kruskal-Walli test was also run, as seen in Fig. 2, to compare the respondents' perspectives depending on their years of experience. Except for "Less accidents and unforeseen circumstances," which revealed that there is a statistically significant difference in the mean values of the respondent category, it was determined that there really is no significant difference in the mean values for any of the benefits.

CONCLUSION

Among the major institutions in the global market is construction. Construction has been slower than other industries to adopt robotics because, as was already mentioned, it is one of the sectors that takes the longest to start down the path of automation and digitalization. A number of things, including the price of labor or the processes’ lack of preparation, causes this. Robotics has several benefits, and it is already used in a number of industries, including architecture, masonry, demolition, and infrastructure. Safety and inspection activities, which employ technology to examine and detect any problems in real time and convey the information to the system so that it can be fixed as soon as possible, are some of the duties that call for succinct use of robots. Robotics will improve the construction sector in a variety of ways, including greater production, decreased mistakes, meeting deadlines, reducing accidents, and lowering prices.

The study suggests that the government step in to fund and provide incentives for construction companies to apply robotic technology in order to make the construction industry appear innovative and efficient rather than outdated and reticent to adopt new technologies. This is because the application of robotic technology is thought to be expensive to implement. If the construction industry is to quickly adopt robotic technology in the South African prefabricated construction industry, big private construction companies must also consider this collaboration and collaborate with the government to educate and train small construction companies, clients, and end-users in this area.

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CONTRIBUTION OF LEAN TECHNIQUES TO INDUSTRIALIZED CONSTRUCTION ADOPTION: A BARRIERS MITIGATION APPROACH

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ABSTRACT

Despite the benefits associated with industrialized construction (IC), it has low overall levels of adoption. IC is an innovation that is not aligned with institutionalized project supply chains; it has implications in process integration that intensify adoption barriers. Several studies have shown the effectiveness of implementing Lean techniques in different stages of the IC process. This paper exposes the analysis of the contribution of implementing Lean techniques to performance, process flow, knowledge management, and value addition. The implementation results are analyzed in terms of their contribution to mitigating the IC adoption barriers identified in the Chilean context. A systematic literature review is carried out to identify the Lean techniques implemented in some of the phases of the IC process. The analysis of the results reported and the contribution of the implementation of Lean techniques to the mitigation of the impacts of some of the existing barriers to the adoption of IC is conducted using thematic content analysis. Thirty Lean techniques are identified whose implementation results are related to the mitigation of conditions associated with 76.5% of the IC adoption barriers considered to be of high and very high impact for the Chilean context.

KEYWORDS

Lean construction, prefabrication, assembly, off-site construction.

INTRODUCTION

Industrialized construction (IC) has been identified as a promising approach to improving project performance. Despite the associated benefits, IC presents an incipient level of adoption and implementation (Jaffar & Lee, 2020), and it still faces immense resistance from the industry and the market (Razkenari et al., 2019). In Chile, the construction industry faces pressures and substantial threats related to the shortage of skilled labor, increased labor costs, the disruption of new competitors, and the postpandemic economic crisis scenario. Due to this, the Chilean

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Chamber of Construction has identified the adoption of IC as one of the three levers that encourage leaps in productivity, along with Building Information Modeling (BIM) and digitization (Matrix Consulting, 2020). However, the adoption of IC in Chilean construction maintains low levels (Construye 2025, 2022).

The adoption of IC is an example of the diffusion of innovation. In the construction industry, the diffusion of innovation is extremely slow due to the adoption processes being carried out amid a complex series of barriers (Wuni & Shen, 2020), which directly affects the perception of the offer of improved utility compared to existing technologies. Because of this, IC implies technological adoption and a cultural management process aimed at reducing the uncertainties associated with the perceived benefits of innovation.

IC is a phenomenon oriented toward the integration of processes, which implies long-term relationships between the different actors, advanced supply chain management, a design oriented to better support the manufacturing and installation phase, and the capture of experience and knowledge management aimed at continuous improvement (Lessing, 2015). It is an innovation not aligned with institutionalized project supply chains. These chains, therefore, require a change in the process that implies that multiple companies modify their practice in a coordinated way (Lavikka et al., 2021). This condition intensifies the difficulty of implementing innovations in project networks that consist of numerous parts and present fragmentation.

Many of the emerging problems in IC implementation experiences are related to the forms of adoption, that is, a focus on the incorporation of industrialized construction systems under a context of organizational structure, project development model, and conventional work methods (Andersson & Lessing, 2017); such characteristics include highly fragmented scenarios, poor communication, information exchange, cooperation and coordination between actors, and using conventional acquisition methods. These adoption conditions lead to failed experiences and unsatisfactory/inconsistent performance results.

Numerous papers have illustrated the contribution of Lean techniques in the domain of supply chain management and the rationalization of construction processes. In the field of IC, various studies have shown the effectiveness of different degrees of implementing Lean techniques in different stages of the process (Innella et al., 2019). Given the above, one of the emerging research directions involves a combination of IC and Lean techniques. However, the systematic analyses described in the literature in this field are insufficient, and there needs to be more clarity about the progress of current research. Therefore, reviewing previous research on implementing Lean techniques in the various stages of the IC process is opportune. Similarly, based on the implementation results, we analyze the contribution of these techniques to performance, process flow, innovation management, and value addition and mitigate the impacts of conditions identified as barriers to adopting IC.

RESEARCH METHOD

A systematic literature review (SLR) was carried out to identify the Lean techniques implemented in the different phases of the IC process. Additionally, a thematic content analysis (TCA) was conducted to analyze the results of the reported implementations and the contribution of the implementation of these techniques to the mitigation of the impacts of some of the existing barriers to the adoption of IC.

The search for related research papers published between 2017 and 2023 was conducted in the Scopus and Web of Science (WoS) electronic databases. The criteria for database selection were based on the fact that these databases are the largest in the field of inquiry; Web of Science has a longer time frame, while Scopus has more recent articles (Chadegani et al., 2013). The search equations were built according to the following combination criteria: TITLE-ABS-KEY (("lean construction" OR "lean practice" OR "lean principles" OR "lean tools" OR "lean strategies" OR "lean techniques") AND ("off-site construction" OR " industrialized building system" OR "industrialized construction" OR "modern method of construction" OR "prefabrication" OR “modular construction)) AND (LIMIT-TO (PUBYEAR, 2017-2023). Through the search strategy, 36 articles were selected from the electronic databases. Following the criteria for the exclusion of irrelevant articles, based on the nonexplicit declaration of Lean techniques or a specific phase of the IC process, seventeen were discarded. The resulting nineteen studies were included in the analysis.

The studies on implementing Lean techniques in IC processes were analyzed from a quantitative and qualitative approach. The quantitative analysis integrated the prevalence of the techniques and results found in the literature. The qualitative study was carried out based on the thematic content analysis (TCA) method to identify relationships between outcomes associated with Lean techniques and IC adoption barriers. The barriers identified by Ortega (2022), with high and very high impacts on the context of Chile, were taken as a basis for the analysis of the contribution of Lean techniques to the mitigation of the impacts of the existing barriers to the adoption of IC.

FINDINGS

LEAN TECHNIQUES IMPLEMENTED IN THE IC PROCESS

Nineteen studies were identified from the literature review that address implementing Lean techniques in different stages of the IC process. These studies, their country of origin, and the associated industrialized system examined are presented in Table 1.

Table 1: Studies resulting from the literature review.

Id.	Authors	Country	Industrialized system
1	(Ahmad et al., 2019)	Malaysia	Precast components
2	(Barkokebas et al., 2021)	Canada	Unspecified
3	(Bataglin et al., 2017)	Brazil	Precast ETO systems
4	(Bataglin et al., 2022)	Brazil	Precast ETO systems
5	(Bortolini et al., 2019)	Brazil	Precast ETO systems
6	(Brown et al., 2019)	Canada	Wall Assembly Line
7	(Chauhan et al., 2019)	Finland	Unspecified
8	(Darwish et al., 2020)	Canada	Panelized Homebuilding
9	(Gbadamosi et al., 2019)	United Kingdom	Design for Assembly
10	(Goh & Goh, 2019)	Singapore	Prefinished volumetric
11	(Heravi & Firoozi, 2017)	Iran	Precast steel frame
12	(Heravi et al., 2021)	Iran	Precast steel frame
13	(Laika et al., 2022)	Iran	Precast concrete
14	(Marte Gómez et al., 2021)	United Kingdom	Unspecified
15	(Peiris et al., 2021)	Australia	Precast components
16	(Placzek et al., 2021)	Germany	Additive manufacturing
17	(Shabeen & Krishnan, 2022)	India	Precast components
18	(Li et al., 2018)	China	Precast components
19	(Xiong et al., 2018)	China	Unspecified

In the studies, thirty implemented Lean techniques were identified. These techniques were grouped according to the purpose of the implementation: identifying and reducing waste, improving flow, adding value, and continuous improvements. Eleven Lean techniques associated with identifying and reducing waste were found, aimed at identifying waste (3), reducing cycle time (1), reducing batch size and work-in-progress (4), increasing transparency (2), and materials management (1). Regarding improving the flow and reducing variability, fourteen techniques were identified aimed at reducing flow variability (1), increasing manufacturing flexibility (2), increasing stakeholder and systems integration (3), improving product and operation flow (2), pull production (2), reducing process variability (2), and leveling production (1). One identified technique was found to be associated with adding value and oriented toward decision-making (1). Finally, regarding striving for perfection and continuous improvements, four techniques were identified (4). Table 2 shows the thirty techniques identified based on the grouping stated, and the ID number of the study (according to Table 1) in which each technique is listed.

Table 2: Lean techniques implemented in the IC process.

	Goal	Techniques	Included by (ID from Table 1)
Identifying and reducing waste	Identifying waste	T1 - Value stream mapping (VSM)	2, 11, 13, 14, 17
		T2 - Genchi Genbutsu (Gemba)	2
		T3-5 Whys technique (RCA)	13
	Red. cycle time	T4 - Total Productive Maintenance (TPM)	12
	Reduction of batch size and work-in-progress	T5 - Takt Time planning	4,14
		T6 - Work-In-Process (CONWIP)	18
		T7 - Location-Based Planning (LBP)	4
		T8 - Line of balance (LOB)	4
	Increasing of transparency	T9 - Visual boards/management	4, 14, 15
		T10-5S	13, 5
	Material mgmt.	T11 - Kanban	1, 10
Improving flow and reducing variability	Flow variability	T12 - Last planner system (LPS)	4, 11, 14
	Flexible manufacturing	T13 - Process modularity (PM)	4
		T14 - Bidirectional workflows (BDW)	16
	Stakeholder and systems integration	T15 - Integrated Project Delivery (IPD)	4
		T16 - Lean Project Delivery (LPD)	14
		T17 - Target Value Design (TVD)	4, 14
	Product and operations flow	T18 - BIM	2, 3, 4, 5, 6, 9
		T19 - Simulation	6, 8
	Pull production	T20 - Just-in-time (JIT)	1, 4, 10, 13, 14
		T21 – On-demand production (ODP)	16
	Process variability	T22 - Mistake proofing (Poka-yoke)	14
		T23 - Cross training (CT)	10
	Leveling the production	T24 - Standardization (Procedure, time,	15
		T25 - Process Specification Language (PSL)	19
Value	Decision-making	T26 - Choosing by advantages (CBA)	7, 14
Continuous improvement	Aiming to perfection	T27 - Kaisen	2
		T28 - First Run study	14
		T29 - Quality Check (QCH)	14, 16
		T30 - Total Quality Management (TQM)	10

Registered implementations are tied to different phases of the production process. A total of 10.5% of the studies report implementations in the design phase, including 6.7% of the identified techniques. The design phase's implementation focuses on adoption decision-making and design for assembly. Off-site production is the phase addressed most frequently; 63.2% of the studies report implementations in this phase, and 63.3% of the identified techniques emerge from them. The implementations reported in the off-site production phase focus on rationalizing the production process. The on-site assembly phase is addressed in 26.4% of the studies, with the implementation of 60.0% of the techniques. The focus of the implementations associated with this phase is to improve the installation process by synchronizing off-site production with on-site production. The most prevalent Lean techniques found in the literature are Building Information Modeling (BIM) (31.6%), Value Stream Mapping (VSM) (26.3%), and Just-in-time (JIT) (21.1%), followed by 5S, the Last Planner System (LPS), and visual boards, which are reported in 15.8% of the studies. Figure 1 presents the prevalence in the literature of the identified Lean techniques.

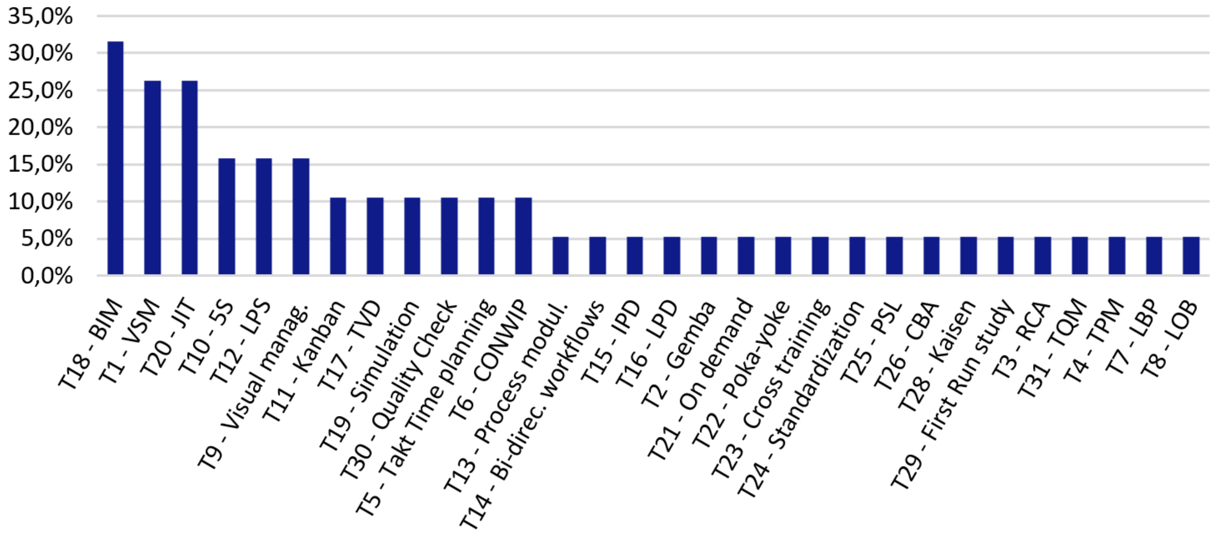

Figure 1: Prevalence of Lean techniques in the literature

RESULTS ASSOCIATED WITH THE LEAN TECHNIQUES IMPLEMENTED

Studies relate specific results to the implementation of Lean techniques. These results can be divided into two categories: diagnostic and interventional. Of the studies, 36.8% report results associated with the possibility of an adequate diagnosis, that is, waste identification from the use of the VSM, Gemba, and RCA techniques.

In terms of the results of the intervention, improvements in the performance process flow, knowledge and labor management, and value addition were identified. A total of 68.4% of the studies report changes in performance indicators. A total of 57.9% of the studies report a reduction in process time. This reduction is associated with lead time reduction (36.8%), cycle time reduction (36.8%), and idle time reduction (47.4%). Likewise, 26.3% of the studies report a decrease in costs; 21.1% mention the reduction of costs related to the off-site production process, 21.1% report total project costs, and 26.3% report labor costs. A total of 21.1% of the studies reported quality improvements linked to the early detection of deviations and eliminating design errors and inappropriate designs. A total of 42.1% of the studies report more significant control over the work in process, 15.8% declare a general improvement in performance, and 31.6% declare an improvement in productivity.

Regarding the improvement of the process flow, studies report results associated with decreased fragmentation among stakeholders and phases of the process. A total of 36.8% of the studies report improvements in terms of early integration and adequate conditions for integration, namely, adequate collaboration among actors from different phases (31.6%) and improvements in communication (31.6%). Linked to these improvements in terms of integration, 26.3% report greater synchronization between design and off-site production, and

15.8% report greater synchronization between off-site production and on-site installation. A total of 5.3% of the studies report a reduction in transport processes.

Some studies report improvements associated with knowledge and labor management. A total of 21.1% of the studies declare a decrease in the complexity of knowledge management linked to the increase in transparency and standardization. Likewise, 15.8% report a reduction in risk at work, and 5.3% report a reduction in training time for the workforce.

Regarding value addition, 15.8% of the studies report that implementing Lean techniques increases the satisfaction level of end users, and 10.5% report that such implementation provides adequate support for decision-making on IC adoption. A total of 22 results were identified, which are presented in Figure 2.

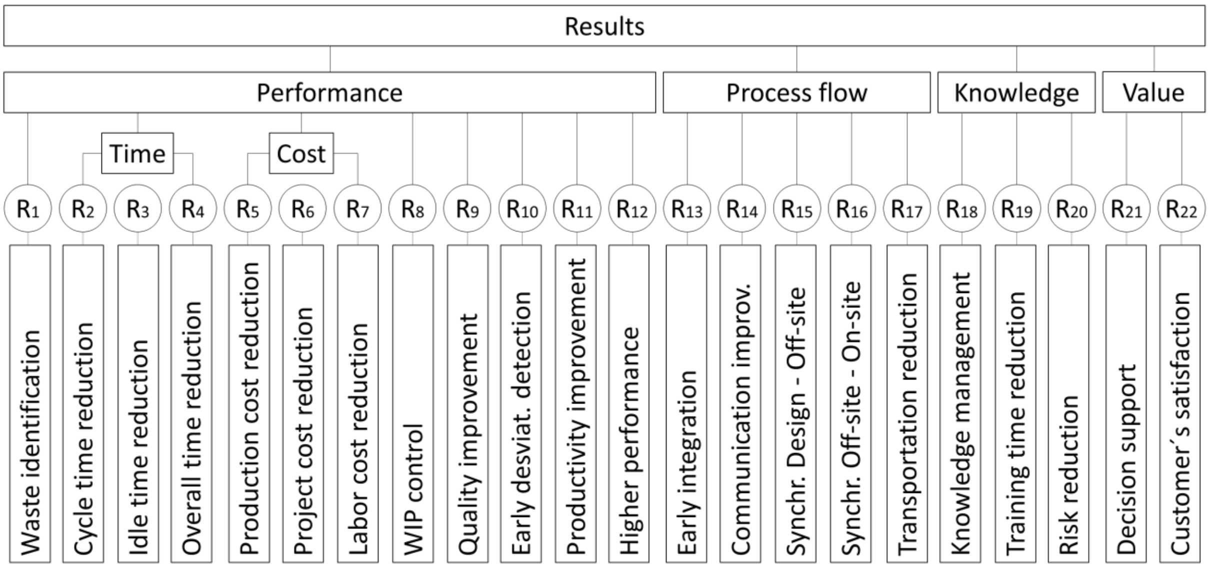

Figure 2: Results of the implementations of Lean techniques reported in the literature.

In 42.1% of the studies, the reported implementation integrates only one Lean technique. In most of these cases (15.8%), the implemented technique is BIM. The CONWIP, VSM, simulation, PSL, and CBA techniques are integrated into the rest of the cases of isolated technique implementations. In 21.1% of the studies, the implementations integrate two Lean techniques; these are simultaneous implementations of JIT and TPM, JIT and Kanban, VSM and LPS, and BIM and simulation. A total of 10.5% of the studies report implementations that integrate three techniques such as bidirectional workflows, on-demand production and quality checks, visual management, 5S, and standardization. A total of 10.5% of the studies simultaneously incorporate four techniques, 5.3% incorporate five techniques, 5.3% incorporate nine techniques, and 5.3% incorporate eleven techniques. It is opportune to point out the form of implementation of the techniques as being either isolated or together since the results reported by the studies result from the specific type of implementation in terms of the confluence of different techniques. Therefore, even though the results attributed to implementing a particular technique can be traced in the studies, there is the incidence of the synergistic effect of implementing multiple techniques to consider. Figure 3 presents the relationship among the identified Lean techniques and the specific results associated with their implementation.

LEAN CONTRIBUTION TO MITIGATION OF IC ADOPTION BARRIERS IMPACTS

Based on the previous relationship between Lean techniques and results, the areas of incidence of these results were analyzed to identify relationships among them and the barriers to IC adoption. That is, we aimed to identify from the results the possible contribution of implementing Lean techniques to modifying the conditions constituted as barriers and, consequently, mitigation of their impact. In previous research (Ortega, 2022), existing IC adoption barriers have been identified, and their level of impact has been evaluated for the Chilean context. The barriers assessed as having high and very high impact have been previously grouped into cultural, quality, market, cost and finance, design and development, innovation and technology, skills, regulations, status, diffusion, and logistics. In the present study, these barriers were analyzed and regrouped based on the possibility of their mitigation from Lean implementations. The authors acknowledge that grouping barriers into typologies is highly subjective and that there may be overlaps between groupings. The proposed grouping seeks to align with the results related to Lean technique implementations.

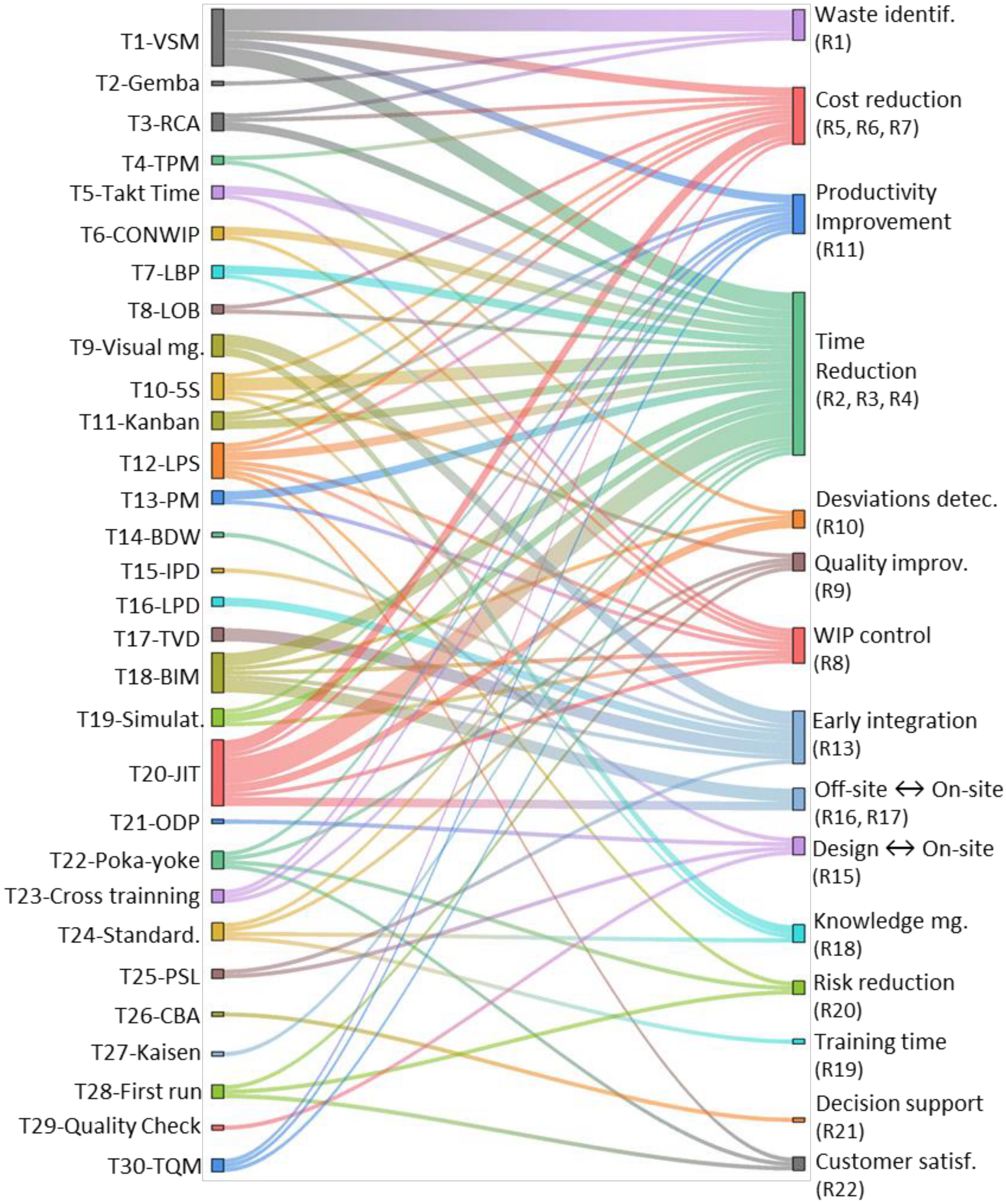

Figure 3: Results associated with Lean techniques.

Initially, the barriers were analyzed based on their dependence on external agents. Sixteen high external dependence barriers were identified, which are related to limitations of offers, demands, regulations, external incentives, financing possibilities, and external actors' IC knowledge. These barriers are as follows: lack of offers from manufacturers, low standardization level of materials/elements, higher and volatile cost of materials, low market demand, low client/consumer/general public acceptance/valuation, unsuitable for small projects, difficulty obtaining financing, lack of regulations, rigid regulations, incompatibility between current and emerging regulations, lack of more demanding quality regulations, lack of quality assessment/accreditation instruments, lack of knowledge on the part of the state, lack of modernization of university curricula, lack of government incentives, and lack of financing for system innovation ventures. These barriers were not included in the relationship analysis with the results related to Lean techniques. However, other barriers with less dependence on external agents were included in the analysis. These barriers were grouped according to their association with performance, process flow, and knowledge management.

Barriers associated with performance.

The barriers associated with performance indicators are as follows: higher overall cost (B1), higher initial costs (B2), higher costs of technology (B3), higher labor costs (B4), difficulty obtaining advances (B5), higher cost of transportation (B6), difficulty in achieving economies of scale (B7), greater economic risk (B8), longer setup times during the planning stage (B9), and longer setup times during the design stage (B10). Eighty percent of these barriers are related to conditions that, according to the results reported, are modified by implementing Lean techniques. Only barriers B3 and B5 are not directly related to any of the results. The result R4, namely, time reduction, is associated with the implementation of VSM, RCA, Takt time planning, COWIP, LBP, LOB, 5S, Kanban, LPS, process modularity, BIM, JIT, standardization, and Kaisen, can help mitigate the impact of barriers B8 and B9. Results R5, R6, and R7, which are linked to cost reduction related to implementing VSM, RCA, TPM, LOB, 5S, Kanban, LPS, JIT, cross training, and TQM, can help mitigate the impact of barriers B1, B2, B4, and B8. The result R7, namely, labor cost reduction, is directly related to barrier B4. The result R15, which is associated with implementing bidirectional workflows, on-demand production, and quality checks, can contribute to mitigating the impact of barrier B7. Result R17, which is related to the implementation of JIT, can contribute to mitigating the impact of barrier B6.

Barriers associated with process flow.

The barriers associated with the process flow are associated with a lack of integration and changes in the process. The barriers linked to the lack of integration are fragmented supply chains (B11), short-term business relationships (B12), inappropriate project delivery models and contracts (B13), poor communication/coordination among stakeholders (B14), and poor collaboration among stakeholders (B15). The results 13 and 14, associated with implementing visual management, LPS, IPD, LPD, TVD, BIM, and PSL, can contribute to mitigating the impact of barriers B11, B13, B14, and B15.

The barriers linked to changes in the process refer to changes in planning and design, off-site production, transportation and storage, and on-site production. The barriers associated with planning and design are as follows: lack of adapted planning and control structure (B16), inadequate approval and quoting processes (B17), incompatibility between traditional and industrialized designs (B18), inability to define/freeze design early (B19), design limitations that affect customization (B20), inflexibility to apply late changes to the design (B21), lack of design standardization (B22), and low investment in the design stage (B23). The result R15, related to implementing bidirectional workflows, on-demand production, and quality checks, can mitigate the impact of barriers B18, B19, B20, B21, and B22. Likewise, the results R21 and R22, associated with the implementation of LPS, Poka-yoke, CBA, and the first-run study, can contribute to mitigating the impact of barrier B20. Despite not being declared as a direct result, the results in performance improvement associated with the implementation of techniques such as LPS, LOB, and LBP, which establish planning and control methods, allow linking these techniques to the mitigation of the B16 barrier.

The barriers associated with off-site production are the inflexibility of production lines to respond to changes (B24), limited productive capacity of suppliers (B25), and poor management and production in the factory (B26). Result R15, which is associated with implementing bidirectional workflows, on-demand production, and quality checks, can contribute to mitigating the impact of barrier B24. Results R11 and R12, which are related to the implementation of VSM, Kanban, LPS, simulation, JIT, Poka-yoke, cross training, and TQM, can contribute to mitigating the impact of barriers B25 and B26.

The barriers associated with transportation and storage are long transport distances (B27), increased transportation restrictions (B28), and the lack of storage and transport quality measures (B29). Result R17, which is associated with implementing JIT, can contribute to mitigating the impact of barriers B27, B28, and B29.

The barriers associated with on-site production are increased site restrictions (B30), low tolerances between precast systems and on-site structures (B31), the predominance of conventional over industrialized processes (B32), and a lack of recognition of indirect construction cost impacts (B33). Result R16, which is associated with implementing BIM, JIT, and PSL, can contribute to mitigating the impacts of barrier B31.

A total of 69.6% of the barriers associated with the process flow are related to conditions that, according to the reported results, are modified by implementing Lean techniques.

Barriers associated with knowledge management.

The barriers associated with knowledge management are related to knowledge, skills and experience, and change and motivation management. The barriers linked to knowledge, skills, and experience are the low documentation of economic benefits (B34), low levels of R&D in the industry (B35), the lack of university-industry joint work (B36), the lack of planning capacities (B37), the lack of technical skills (B38), the lack of skilled labor (B39), the lack of capacities to adopt technology and innovation (B40), the lack of capacity to objectively benefit assessment (B41), inadequate education and training (B42), the lack of capacity to synchronize off-site and on-site activities (B43), the lack of previous design experience (B44), the lack of previous on-site management experience (B45), and the lack of previous construction experience (B46). Results R11 and R12, which are associated with the implementation of VSM, Kanban, LPS, simulation, JIT, Poka-yoke, cross training, and TQM, can contribute to mitigating the impact of the B37 barrier. Results R18 and R19, which are related to implementing visual management, 5S, and standardization (procedures, time, quality), can contribute to mitigating the impact of barriers B38, B39, B40, and B42. Result R10, which is associated with the implementation of TPM, BIM, and JIT, and result R15, which is related to the implementation of bidirectional workflows, on-demand production, and quality checks, can both contribute to mitigating the impact of the B44 barrier. Result R16, which is associated with implementing BIM, JIT, and PSL, can contribute to mitigating the impact of barriers B43, B45, and B46.

The barriers linked to change and motivation management are the lack of support for adoption (B47), negative perception of failed experiences (B48), the lack of IT adoption (B49), the lack of BIM adoption (B50), and resistance to change (B51). Result R21, which is associated with implementing CBA, can contribute to mitigating barrier B47.

A total of 72.2% of the barriers associated with knowledge management are related to conditions that, according to the reported results, are modified by implementing techniques. Some of the barriers not considered in the field of incidence of the reported results, such as low documentation of economic benefits (B34), can find mitigation in the study of the phenomenon of IC adoption and strategies aimed at improving implementations, such as the studies considered in this document.

CONCLUSIONS

This research conducted an SLR of the Lean techniques implemented in the IC process, using the Scopus and Web of Science (WoS) database. The literature review results showed thirty Lean techniques whose implementation modify conditions associated with 76.5% of the IC adoption barriers considered high and very high impact for the Chilean context, and based on this, could contribute to mitigating the impact of the barriers on adoption scenarios.

The contribution of the implementation of Lean techniques in the cases studied is based on several factors: (i) the rationalization of the process associated with the identification and reduction of wastes, which leads to an improvement in performance indicators (cost, time, quality, productivity) and contributes to reducing the negative perception related to failed experiences and unsatisfactory and inconsistent results; (ii) the reduction of fragmentation, which is associated with greater early integration, better communication and collaborative work, and greater synchronization between phases, both between design and off-site production, as well as production or off-site and on-site installation, and (iii) the management of knowledge and change.

Research efforts in the field of IC management, from a Lean approach, are concentrated in the off-site production phase. A total of 63.2% of the studies, from which 63.3% of the implemented Lean techniques emerge, have this phase as a focus of interest. The number of studies focused on IC design management and construction site management, from implementing Lean techniques, is limited.

The approaches based on integration include integration among actors of a phase and among phases of a project, while practices aimed at reducing the level of fragmentation between projects are not identified. The techniques reported as IPD, LPD, and TVD are framed at the project scale. The adoption of IC by construction companies implies establishing a structure to manage continuous processes to develop and manage their production system and the associated subsystems, as well as the execution of construction projects. This approach that integrates continuous processes and discrete projects requires different technical systems, organization, processes, and supply chains than traditional construction companies. The approach to overcoming the B12 barrier, namely, short-term business relationships, implies not only integration at the project level but also the search for solutions to the loss of tacit knowledge, with a focus on how to work together effectively after the dissolution of the teams at the end of the projects. This aspect emerges as a field of potential contribution of Lean techniques not addressed in integrated studies.

The current document contributes to the body of knowledge on IC management by discussing the implementation of Lean techniques and their contribution to mitigating adoption barriers. Likewise, in terms of practical contribution, it identifies specific Lean techniques that can be integrated into different phases of the IC process and links them to results that modify conditions associated with adoption barriers. These findings constitute input based on the proposition of implementations that utilize a Lean approach that, based on performance improvement, process flow, knowledge management, and value addition, contributes to reducing the number of uncertainties associated with the perception of the improved utility of IC versus conventional construction and, consequently, to mitigating barriers to IC adoption.

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THE IMPACT OF AN OFFSITE PRODUCTION APPROACH ON MECHANICAL AND ELECTRICAL PROJECTS: EVIDENCE FROM THE UK

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ABSTRACT

Previous studies have reviewed the impact of offsite production on the delivery of construction projects, however, there have been limited studies examining the specific impact of offsite on mechanical and electrical installations (M&E). Therefore, the aim of this study was to determine the impact of offsite production in the delivery of mechanical and electrical installations for construction projects. In this study, a mixed method was adopted, using quantitative data obtained through a questionnaire survey and qualitative data through case study interviews. In total, primary data was collected from 36 questionnaire responses, and 3 case studies that involved 12 in-depth interviews.

This study shows that offsite production has a positive impact on construction project performance indicators for M&E installations regarding factors such as time, quality, health and safety, sustainability, logistics, and collaboration. However, the study showed no general conclusion as to the cost saving impact of offsite construction on the outcomes of projects. Nevertheless, the study established that the offsite approach offers the client more confidence relating to cost certainty.

Recommendations from this study are that offsite production should be selected based on its impact on project performance indicators rather than cost alone. The study argued that the offsite production method should be explored as much as possible when maximal benefits are sought; however, it should not be utilised simply for the sake of it but on a case-by-case basis.

KEYWORDS

Offsite construction, prefabrication, assembly, modular construction, M&E installations.

INTRODUCTION

Offsite production is a modern method of construction (MMC), often referred to as 'prefabrication' 'pre-assembly' or 'modularisation'. It is the process of completing construction elements away from the physical site in a controlled facility; to achieve time, cost, quality, health, and safety efficiencies (Vurren, 2020). In recent years, offsite has increased interest due to increased utilisation of Building Information Modelling (BIM) (Farmer, 2016). According to Sherratt, Dowsett and Sherratt (2020), the current concerns of the Global Construction

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Industry are labour shortages and the demand for shorter construction programmes, heightening the need for innovative modern construction methods such as offsite production. Offsite production can achieve material efficiency, reduce waste, reduce timescales on site, improve health and safety and reduce disruption to construction projects (Hough, 2019). The UK Construction industry is being pushed to modernise and innovate, with Farmer (2016) stating the industry-wide issues of low productivity, low margins, an ageing workforce and lack of research and design. Samarasinghe et al. (2019) claim the past decade has seen a growing trend towards the offsite production of M&E systems.

Extant literature shows a range of information about adopting offsite in the construction industry. Smith and Quale (2017) focus on the theory and practicality of offsite concerning the demand for housing. Court, Pasquire and Gibb (2009) observe offsite as a solution for the UK's health, safety, and productivity issues. Marte Gómez et al. (2021) note the effects of implementing offsite construction within the UK housing sector. Sutrisna, Ramnauth and Zaman (2020) highlight the competitive advantages and risks of offsite production on construction projects.

In contrast, there is less information on adopting offsite for M&E installations. Said (2015) discusses best practices for offsite production; however, the paper focuses solely on electrical installations. Korman and Lu (2012) research focuses on the link between M&E but with a specialisation on the improvement in BIM. Although M&E installations contribute 40-60% of the total construction costs (Guo, Wang, and Park, 2020), limited studies have explored the impact of offsite construction in delivering M&E projects. Given this, this study aims to identify the effects of the offsite process on time, quality, safety, and cost in M& E projects in the UK.

The key research question is: **What is the impact of offsite production in the delivery of mechanical and electrical installation aspects in projects?** With the following research objectives:

- To review the current knowledge relating to the use of off-site production on the M&E sector.
- To determine the impact of utilising offsite production, relating to project performance indicators and cost, on M&E projects.
- To draw conclusions from the findings and provide a decision on the suitability of using offsite production in the M&E sector.

Findings from this study are that offsite production should be selected based on its impact on project performance indicators rather than cost alone. With the argument that the offsite production method should be explored as much as possible when benefits are achieved; however, it should not be utilised simply for the sake of it but on a case-by-case basis. This research will help organisations understand the effects of offsite approach construction on delivery and performance indicators in M&E projects.

LITERATURE REVIEW

INDUSTRY VIEW OF OFFSITE CONSTRUCTION

According to Agarwal, Sridhar and Chandrasekaran (2022), the construction industry is subject to change; projects can take up to 20% longer than programmed and cost 80% more than budgeted. Ren, Atout, and Jones (2008) research suggest that main contractors are the root cause of 62% of project delays, consultants 27% and clients 11%. Common issues include poor communication, incomplete drawings, and compressed programmes. Agur, Chipatpo and Thom (2015) describe how offsite construction can impact projects by improving productivity, collaboration, and skills.

The key reports relating to the UK Construction Industry are of Latham (1994), Egan (1998), Wolstenholme (2009) and Farmer (2016). The recommendations offered by these reports are primarily the same: standardisation and offsite. The House of Lords (2016) also suggests that offsite production could be the solution that would help the UK Government achieve its 2025 targets of 33% reduction in construction cost, 50% reduction in programmes and 50% reduction in greenhouse gasses.

CURRENT KNOWLEDGE RELATING TO THE USE OF OFFSITE PRODUCTION IN M&E

Guo, Wang, and Park (2020) discuss how M&E installations contribute 40-60% of the total construction costs. Issues affecting the installation of these systems include interface with the other trades on-site and general issues facing the industry, such as dangerous weather conditions and quality control. Sands and Quale (2019) specify further problems with M&E installation, such as limited space, health and safety and demanding programmes. Guo, Wang, and Park (2020) continue with, for the reasons described above, M&E installations are increasingly taking an offsite approach to delivery. Wilson, Smith, and Deal (1998) summarise that all projects utilising an offsite system to M&E have benefited. However, this must be balanced with the drawbacks. According to Goulding and Pour (2019), low design standardisation reduces the uptake. Farmer (2016) believes reluctancy is due to clients being unwilling to finalise designs at an earlier stage, a crucial requirement of offsite production.

METHOD

The research method adopted for this study was a mixed-method approach including triangulation (Palinkas et al., 2015). A questionnaire was used to gain quantitative data, and a case study analysis was used to gather qualitative data. According to Breach (2009), case study analysis is instrumental in collating ideas and perceptions. This was applied to obtain further in-depth information on how offsite is adopted on live and completed M&E projects.

RESEARCH DESIGN

The study commenced with a literature review, which according to Naoum (2019) is to create a focus for the data collection. The research instrument utilised for the subsequent quantitative phase was an online questionnaire survey administered via ‘Google Forms’., Naoum (2019) suggests that this method increases the number of responses. The questionnaire was designed to be short and engaging, with 13 number close-ended questions relating to findings from the literature review and research objectives. An example of a question was, “Off-site is more cost effective in comparison to traditional on-site delivery of M&E installations". Please indicate your opinion of the above statement by ticking the appropriate response”.

However, an additional 5 number open-ended questions were included to connect to the findings from the interview. An example of one of these questions was “What recommendations would you have for someone considering off-site production for the M&E installations on their next project?”.

Firstly, the questionnaire was piloted with three industry professionals before data collection; according to Fellows and Liu (2015), this ensures the questionnaire is easy to understand and provides the opportunity for amendments. Purposive sampling was applied in this study, given that a limited number of people are available in this research area (Palinkas et al., 2015). According to The UK offsite Hub and Building and Design, the number of offsite construction organisations in the UK is 228 number. Using a confidence level of 90% and a margin of error of 10%, a sample size of 53 was determined. The questionnaire received 36 responses, 68% of the sample size. The questionnaire was live from the 1st until the 31st of March 2021.

CASE STUDY ANALYSIS

Case studies give a complete picture by drawing on multiple sources of evidence. Knight and Ruddock (2008) suggested that case study analysis is relevant for construction-driven research as the industry is project-specific. Following Yin (2018) the decision was made to utilise multiple (3) case studies for this study and adopt the unit analysis of the interview. This was to understand the real-life adoption of offsite M&E and the opinions of those involved in these projects. The M&E organisation utilised for this study is a national sub-contractor with an offsite manufacturing facility in the UK.

A mixture of 12 project participants from roles that included: Quantity Surveyor, Project Manager, Planner and offsite representative were selected to undertake the interview. The participants were selected based on their experience and active involvement in the case study projects. The case studies and project participants interviewed were selected utilising justified sampling, the 3 projects were selected as they used offsite methods, were completed within the past 12 months and were of a M&E value of £1m or over.

Below is a summary of the case studies assessed as part of this research.

- Case Study 1 (CS01) - This project was a £3m M&E installation in an educational building.
- Case Study 2 (CS02) - This project was a £11m M&E install in a leisure facility.
- Case Study 3 (CS03) - This project was a £2m M&E installation in an educational building.

The interviews were kept open, which created the flexibility to ask the interviewee for further details. Each interview was targeted to be 60 minutes long, utilising online video communication tools Microsoft Teams. Examples of questions asked during the interview are as follows: "What in your opinion are the benefits of utilising off-site on this project?", "What in your opinion are the downfalls of off-site on this project?" and "What is your overall opinion of the use of off-site for M&E?". Ethical approval was obtained before the data collection.

To manage the data analysis process, Creswell, and Poth's (2018) five step process was applied throughout the data collection stage. Silverio-Fernandez, Renukapppa and Suresh (2019) suggest that this methodology creates a deeper understanding of the completed interviews and a more straightforward way of extracting themes. Steps 1 to 4 were applied: recording and transcribing each interview, reading, and reviewing each transcript and making notes of any emerging themes, colour coding to organise transcripts into segments and finally, creating a summary of responses related to themes and producing meaningful information. To maintain confidentiality, the approach adopted to code the case study interviews followed that of Daniel et al., (2018). The case studies are referred to as 'CS01: P01' where C is case, S is study P is a participant. Table I lists each participant's job role, experience, and case study involvement.

Table 1: Case Study Participants

Participant Information				**Case study involvement**		
Participant Code	Job Role	Years' Experience	Employment	CS01	CS02	CS03
PC01	Project Manager	10	M&E Sub-Contractor	Y		
PC02	Planner	32	M&E Sub-Contractor		Y	Y
PC03	Quantity Surveyor	20	Offsite Manufacturer		Y	Y
PC04	Factory Manager	13	Offsite Manufacturer	Y	Y	Y
PC05	Commercial Manager	40	Offsite Manufacturer	Y	Y	Y
PC06	Project Manager	40	M&E Sub-Contractor			Y
PC07	Estimator	45	Offsite Manufacturer	Y	Y	Y
PC08	BIM Manager	25	Offsite Manufacturer	Y	Y	Y
PC09	Project Engineer	6	M&E Sub-Contractor			Y
PC010	Project Manager	20	M&E Sub-Contractor		Y	
PC011	Quantity Surveyor	6	M&E Sub-Contractor	Y		
PC012	Quantity Surveyor	4	M&E Sub-Contractor			Y

Miles and Huberman (1994) suggested that interviewing project participants should continue until saturation of answers was achieved. As no new themes or ideas were emerging within interviews 10 to 12, the project interviews concluded at this point.

The results from completed questionnaires and case study interviews are presented and discussed in the next section.

RESULTS AND DISCUSSION

This section presented and discussed the results of the data collected from both the questionnaires and the interviews.

RESPONDENT BACKGROUND

The 36 respondents to the questionnaire consisted of '22.2% Project Managers', '22.2% Engineers', '22.2% Quantity Surveyors', '8.3% Commercial Managers', '5.6% Planners', '2.8% Academics', '2.8% BIM Managers', '2.8% Estimators', '2.8% Factory Managers' and '2.8%

Team Leaders'. The results also showed that the respondents have varied backgrounds, are employed by different organisations, and have experience working in various sectors. 61.2% of the respondents had over ten years of experience, 89% had worked on projects utilising offsite construction for construction elements of the build, and 86% had experience working on projects using offsite for the M&E aspects of the build.

Like the questionnaire, the case study interview participants were of the same roles and level of experience. This shows that the projects and participants had sufficient knowledge, breadth and experience relating to M&E works and offsite construction; therefore, they were qualified in relation to this research.

THE IMPACT OF OFFSITE PRODUCTION ON M&E INSTALLATIONS

To understand the impact of offsite production in M&E installation, questionnaire respondents were asked to respond using the five-point Likert scale. The results of the analysis are presented in Figure 1. In summary, the questionnaire concludes that most respondents believe that offsite production has a positive on the project performance indicators listed concerning M&E installations.

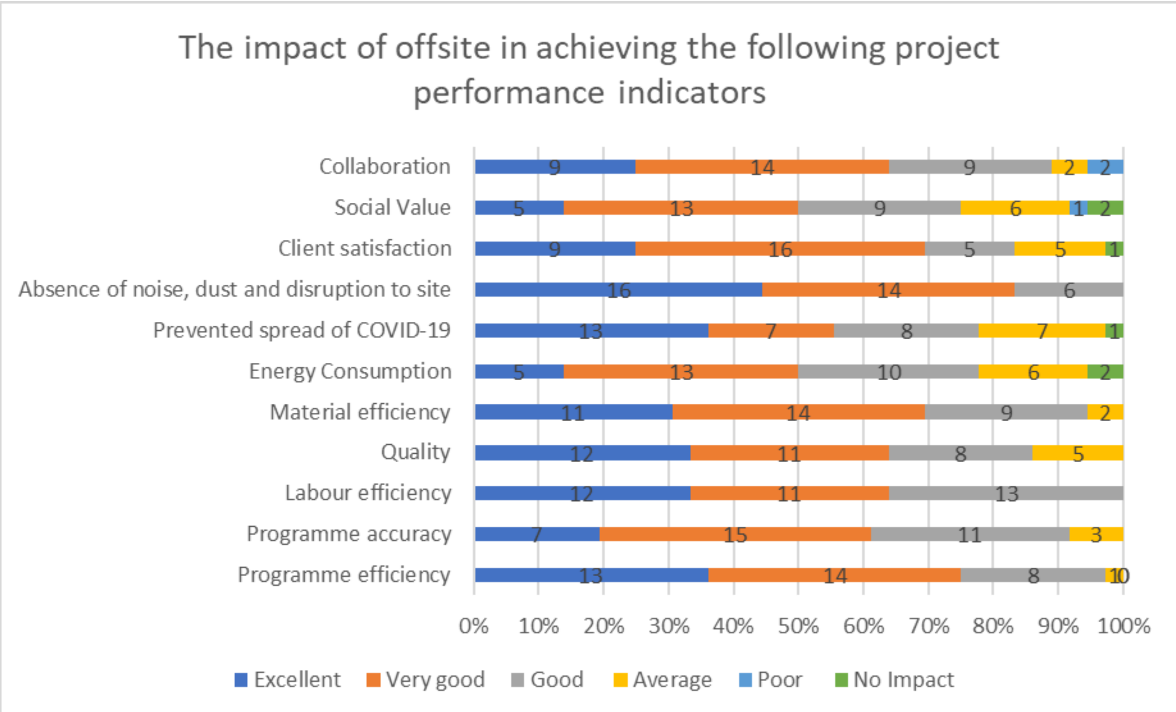

Figure 1: The impact of offsite production in achieving project performance indicators.

The findings from the 12 interviews were grouped into six sections and compared with the questionnaire and literature findings.

TIME

P01 described the impact of offsite on CS01 as saving "6,000-man hours on site and installation of the modules were four times quicker than traditional". The interviews also found that the utilisation of offsite can lead to elements of the installations being completed concurrently with on-site works such as demolition, resulting in M&E installations being able to start on-site later to achieve the same completion date. This creates programme certainty as elements of the programme subject to delay have been removed from the site. Similar findings have been shown in the questionnaire, whereby 97% of respondents believed that offsite has a good or above impact on programme efficiency and 92% respectively relating to programme accuracy. The results found in this investigation are like those of other researchers. Smith and Quale (2017) describe how offsite production can reduce time on site, and Farmer (2016) discusses how offsite can improve labour productivity.

QUALITY

P09 describes how offsite can achieve better levels of quality, "It is easier to build in a factory compared to onsite". The interviews also found that offsite can improve M&E installations' quality through works being completed in a more controlled environment, with quality control checks such as witness, and pressure testing being conducted to the system before delivery to the site. P02 adds, "Offsite production also limits the systems, such as modules and risers, exposure to other trades, reducing damage to the works". The interview findings are comparable to the questionnaire result; 86% of respondents agreed that offsite production positively impacts the quality of M&E installations. This is in line with Sands and Quale (2017) description of how offsite can ensure that the right conditions for tasks are achieved, which leads to an improvement in quality. This is supported further by Farmer (2016) suggestion that offsite production is a more design focussed approach allowing a focus on quality.

HEALTH & SAFETY

The findings from the case study interview were that offsite production positively impacts a project's health and safety. P09 states that "a reduction in the amount of labour on-site reduces the accident frequency", P01 builds on this by saying, "offsite production reduces the spread of transmissible illnesses such as COVID-19". The achievement a higher standard of health and safety could be attributed to offsite works being completed in a controlled facility. This is as offsite enables containment, pipework, and wiring to be completed at a work-bench level compared to ceiling level, eliminating the need for access equipment, and reducing the potential of falls from height. Hot works such as soldering and welding can be completed offsite, reducing risks to other trades. This is supported by Court, Pasquire and Gibb (2008), in which it is detailed how prefabricating M&E modules create the need for mechanical lifting to position these modules, reducing manual handling and the risk of injury. This is additionally supported by Fraser et al. (2015) suggestion that by moving a proportion of the site installation works to a lower risk environment, the project injury rate would reduce.

SUSTAINABILITY

The interviews highlighted that an offsite facility could achieve sustainability better than on-site, P09 details how "the facility has the resources available to implement re-use of materials which may have been over-ordered and create clear segregation of waste promoting recycling". This is supported by Farmer (2016) suggestion that offsite creates standardisation therefore reducing material waste. Additionally, 75.5% of the questionnaire respondents agreed that offsite positively impacts sustainability. Oakley (2017) found that offsite production can reduce CO2 tonnes and reduce material wastage.

LOGISTICS

P02 details how offsite construction was necessary for CS03 as "location of the site was in a built-up area with limited parking; therefore, would not be possible to complete construction of the packaged plantroom". P02 details how offsite construction was also necessary for CS02: "The site was located in a busy residential area, allocating a proportion of the work to an offsite factory reduces congestion in that area". This builds on findings from Farmer (2016), showing that a reduced on-site programme positively impacts noise, air, and traffic pollution, which usually affects the neighboring residents to construction sites.

Collaboration

Surprisingly, collaboration was not discovered in the literature review, this being a sub-theme developed from this research. CS01:P08 described how a "traditional approach to M&E installations lends itself to becoming packaged into sub-contract elements. This is in contrasts to an offsite approach which encourages more collaboration allowing parties to discuss elements of the design which may not have been considered previously until site install. This is in line with the questionnaire findings, where 88% of respondents believed that offsite has a positive impact.

The cost impact of applying offsite production on M&E installations

The questionnaire respondents were asked why offsite production may be more expensive compared to a traditional installation. The four themes developed were design, offsite facility costs, logistics and additional materials.

The responses received have been built on through the interview responses. Like questionnaire findings, P01 details how "BIM and logistics costs are increased compared to a traditional install". P08 adds that material costs increase in an offsite build as "everything offsite is to be enclosed within a steel frame; this adds additional expense". Other findings from the case study interview were that transportation costs increased as materials must be delivered first to the offsite facility and then delivered to the site in their refined form. Additionally, heavy equipment will be required for lifting and positioning on-site. According to Court, Pasquire and Gibb, 2008), lifting and transportation increase offsite costs. The current study identified other costs associated with offsites, such as frame costs, storage, and coordination costs.

The overall impact of offsite on cost

To conclude on the overall impact on cost, the questionnaire respondents were asked to indicate their opinion on the following statement, "Offsite is more cost-effective in comparison to traditional on-site delivery of M&E installations". The majority (47%) of people believe offsite production has a neutral impact on the cost of M&E installations. The second highest response (33%) was that offsite is more cost-effective. This differs slightly from the findings from the case study interview. The overall opinion of the interviewees is that offsite production is either cost neutral or more expensive compared to a traditional approach. This suggests that there is no explicit agreement that offsite creates cost savings. Within the literature review Court, Pasquire and Gibb (2008), Wilson, Smith, and Deal (1998) and Dicks (2002) all suggest that offsite production can offer cost or time-related cost savings. This research suggests slightly different findings, that offsite can be but is not always the most cost-effective approach. This implies that an offsite method is not selected based on cost alone but factors such as labour efficiencies and reduced programme.

The questionnaire respondents were asked about the most essential cost-benefit of offsite production to further understand the reasons for cost savings. 42% of the respondents believed that this benefit was through achieving labour efficiencies and 31% by reducing time-related costs. This mirrors that of Dicks (2002) view that offsite reduced time-related expenses and Court, Pasquire, and Gibb's (2008) suggestion that offsite production reduces labour losses. The remaining 27% of responses were cost certainty, reduced defects, reduced time-related penalties, and reduced life cycle costs.

The case study interview responses show a more detailed understanding of the cost benefits. P08 details how "cost savings can be achieved through an offsite approach by utilising out-of-town low-skilled workforce. This can be compared to a skilled pipefitter from London compared to an out-of-town facility". P02 uses the example of CS03 Packaged Plantroom to describe cost savings. "Modularisation may result in increased costs to the M&E contractor in the case of a plantroom as it includes cladding, concrete base, roof, flooring etc. However, overall savings can be seen on the project cost as a whole”. P05 says that “offsite may be a more expensive approach when the assessment is first completed; however, the process involves considering aspects of the installation that is often not considered until construction, therefore reducing the overall build cost”. Further findings from the interview were that the process of offsite construction includes a much more detailed analysis of costs which considers elements of the construction that may have previously been missed. This implies that offsite construction may improve the level of cost certainty.

CONCLUSIONS

This investigation aimed to explore offsite's impact in delivering M&E installation projects. To achieve the aim of this study, a mixed method was utilised. The study found that offsite production positively impacts the delivery of M&E projects, as demonstrated by the impact on project performance indicators such as time, quality, health and safety sustainability, logistics, and collaboration. However, in terms of cost impact, the respondents have no concession on this. The overall opinion of the interviewees is that offsite production is either cost neutral or more expensive compared to a traditional approach. However, this evidence does not align with a previous study by Pasquire and Gibb (2008). From the evidence gleaned from this study, it can be argued that there is no explicit agreement that offsite creates cost savings. Nevertheless, the study found that the detailed process associated with the offsite approach could give the client the confidence of cost certainty. Additionally, the study found that a more detailed understanding of offsite production's positive and negative implications on M&E installations is essential in costing it.

This study contributes to the future application of offsite production in the construction industry. First, the study has shown that offsite production should be selected based on its impact on project performance indicators rather than cost alone. The study argued that the offsite production method should be explored as much as possible when benefits are achieved; however, it should not be utilised simply for the sake of it but on a case-by-case basis

The limitations of this research were that there was not enough cost information available to compare a traditional and offsite approach based on these findings. Future studies should investigate a detailed cost comparison between offsite production and traditionally installed elements of either M&E or other installations within the build.

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OFF-SITE/ON-SITE COMPOSITE CONSTRUCTION METHOD: AN UNCONSCIOUS LEAN CONSTRUCTION PRACTICE

Jeferson Shin-Iti Shigaki[1] and Tomonari Yashiro[2]

ABSTRACT

This paper provides a contemporary outlook on the concept, features, and achievements of the composite construction methods (fukugōka kōhō) developed in Japan between the 1970s and 1990s. The topic has not been widely publicised abroad, contrasting with prefabricated housing and construction robotics research conducted in the same period. However, the "compounding" approach can play a pivotal role in overcoming the present-day challenge of making digital construction technically possible and economically feasible. This research has employed two research methods. The first was a bibliographic survey of historical construction records and academic articles to grasp how fukugōka kōhō helped construction firms to deal with the pressing business and technological needs of that time. The second was focus group interviews with experienced engineers who came across the yielding effects of the compounding strategy and are now developing and implementing new elemental technologies integral to "smart construction systems" as part of R&D initiatives and productivity improvement management policies, which are tacitly lean. The awareness that try-out implementations of digital construction methods reassemble those past experiences put light on the possibility of resurging lean-ish hybrid production models to ensure competitiveness and reliability advantages in the transition period of technological maturation.

KEYWORDS

Fukugōka kōhō, prefabrication, off-site construction, work structuring, lean construction.

INTRODUCTION

The concept and technology of composite construction methods (*fukugōka kōhō*) emerged and flourished in Japan between the 1970s and 1990s. The fundamental idea was to combine conventional construction methods (*zairai kōhō*) and industrialised construction methods (*kōgyōka kōhō*) to improve the productivity of construction sites in the face of a chronic shortage of specialised construction workers (Nishida and Eguchi, 1989). Thus, it resulted from combining diverse construction technologies, promoting off-site production while maintaining the reliability of established on-site techniques in critical construction parts.

Previously existing composite structures (*gōsei kōzō*), by contrast with single-type counterparts, took the best of each material to respond to earthquake resistance requirements and high performance for realising skyscraper construction (AIJ, 1985). In turn, *fukugōka kōhō* combined the "off-site/on-site" production strategies with specific structural material settings.

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The *fukugōka kōhō* approach gained track when contractors perceived the technical and logistical difficulties of shifting directly to "purer" prefabrication (Takada, 1999).

Thus, *fukugōka kōhō* set realistic alternatives to tackle issues left unsolved by the desired but not all-rounded prefabrication schemes (Eguchi et al., 1988). For example, precast slabs did not eliminate local operations because the connection components remained as on-site manual work. Also, building pathologies, such as water, air, and sound leakage, compromised performance and durability. Thus, contractors preferred to continue employing conventional (by extension, more reliable) techniques in specific components and critical building interfaces.

Prototypical attempts of *fukugōka kōhō* focused on reinforced concrete (RC), steel frame reinforced concrete (SRC), and steel frame (S) structural systems. They usually strived to adopt as many precast concrete (PCa) elements as possible into the constituent parts of a conventional RC Rahmen structure (Ueno et al., 1989). The reasons for adopting it varied according to the requirements and conditions of each project. They included time shortening, reduction of personnel on-site, the downsizing or eventual elimination of temporary installations, reduction of material waste and energy consumption, quality improvement, and safety assurance (Konishi et al., 1996). The expected effects should fit the management targets of QCDSE (Quality, Cost, Delivery Time, Safety, and Environment).

Such strategy, resulting from selecting different construction methods in the same project, conveyed direct implications to structural design (type, properties, and composition of structural parts) and construction planning (construction zone division, erection sequence, assembly techniques, and temporary equipment allocation). The tentative plans employed high-variety low-volume parts to respond to design-construction conditions flexibly, simplifying work composition, nurturing multi-skilled workers, and enabling JIT (Kato et al., 1995).

Composite construction method plans resulted from disassembling, re-aligning, and integrating technologies concerned with construction work division, temporary equipment allocation, and labour assignment (Yashiro et al., 1993). The task of picking up features of existing methods considered the building use, construction site environmental conditions, gemba management policies, and the contract's ability to design technology interfaces between subsystems conceived independently (Takada, 1997). Contractors believed that accumulating improvements would lead to more robust and reliable structures in future projects.

The fact that *fukugōka kōhō* is not discussed under these terms today does not mean it has failed as a technology strategy or management concept. R&D projects were discontinued when the Japanese national economy stagnated after the "bubble economy" burst (Konishi et al., 1996). Then, many construction firms have resumed adopting conventional methods by default, while some suppliers have specialised in prefabrication for specific situations.

However, new technologies pledging to improve on-site operations have transformed the supply chain. Therefore, a revival of *fukugōka kōhō* is arguably an opportunity to promote innovative construction with productivity and personalisation advantages, satisfying both the customer and the production organisation. Digital platforms have significantly evolved, providing a comprehensive set of manufacturing, assembly, and inspection technologies unavailable by that time. The R&D initiatives, like those linked to the Construction RX Consortium, are a case in point (Construction RX Consortium, 2023). On the other hand, Lean Construction principles have been consolidated and can now offer an improved ground to establish better processes for both prefabrication and on-site digital construction schemes. Still, it seems that Japanese firms have handled them unconsciously or tacitly.

This research aimed to introduce the concept of *fukugōka kōhō* to the "outside world" with a refreshed outlook that helps identify drivers and potential barriers to future construction systems seeking to balance technical possibility and economic feasibility, taking advantage of the Japanese experience in developing and deploying composite construction methods.

RESEARCH SIGNIFICANCE

Japanese building construction is acknowledged for its quality and production efficiency. However, most studies disclosed outside Japan have focused on the housing sector, associated with the keywords “prefabrication”, “unit construction method”, and “modular construction”. The seminal papers of Groàk (1993) and Gann (1996) diffused their impressions of missions to Japan to assess the development of prefabricated housing technologies in the 1990s. They did it from an “outsider perspective” through site visits, document analysis, and interviews.

The works of Yashiro (2014) and Matsumura et al. (2019), who interacted with those groups, are some of the few reports published in English conveying a “domestic view”. The ZEMCH network, led by Noguchi (2016), has spread and popularised information about Japanese prefabrication, but they often recall the specific examples of the modular housing niche.

By contrast, the practices of Japanese General Contractors remain somewhat “mysterious” to the international community, given the limited number of sources about them. Foreigner researchers are aware of their technological strengths but know little about them. Bennett (1993) also visited Japan on technical missions and explored this niche. He emphasised the efficient production systems of the leading firms known as the “Big Five” (Kajima, Obayashi, Shimizu, Taisei, and Takenaka), praised for their massive research and development programs. Another notable yet rare case was the work of Bock (1989), who collected, organised, and diffused information in English about prefabrication and construction automation from housemakers to general contractors in rich detail due to the long-term nature of his stay in Japan.

Nevertheless, almost no research about composite construction methods has been published outside Japan. Evidence could be found in domestic papers and magazine reportages of that time. Although the peak of project implementation dates to the second half of the 1980s, the most relevant articles appeared in the early 1990s, based on the accumulated trial and error experience. The case of *fukugōka kōhō* was not limited to the Big Five. Semi-large and mid-sized firms also developed their authored versions and achieved positive results.

Current R&D programs promoting digital construction have set visions of not shifting directly to “purer robotisation” but establishing human-machine partnerships to reduce human labour. Arguably, lessons from the achievements and hardships of *fukugōka kōhō* could be used to set evidence-based R&D programs and support early-stage decision-making. Thus, there are reasons to revisit the *fukugōka kōhō* experience from a contemporary outlook.

RESEARCH PROCESS AND SOURCES OF EVIDENCE

The first part of this investigation identified the characteristics of *fukugōka kōhō* through a historical review to generate insights that could be revived today.

The bibliographic survey employed a triangulation strategy, uniting the academia and industry standpoints. The first source was the “*Sekō: kenchiku no gijutsu = Architectural product-engineering*” magazine series by *Shokokusha Publishing Co*. The second was the annual proceedings of the *Kenchiku Seisan Symposium* (Symposium on Building Construction and Management of Projects) sponsored by the Architectural Institute of Japan (AIJ). The third was a selection of miscellaneous papers from the AIJ database.

Table 1: Sources of the bibliographic survey

Source	Emphasis	Articles (no.)
Sekō: Kenchiku no Gijutsu (1966-2001)	Industry-centred	35
Kenchiku Seisan Symposium (1985-2021)	Industry-academia	10
AIJ miscellaneous papers (1989-1995)	Academia-centred	15

The second part attempted to understand the evolution of the characteristics of composite construction methods over time and the reason for their modifications through focus group interviews with veteran engineers. The target of this study was five prominent Japanese construction firms that developed and employed composite construction methods in the past. Three belong to the so-called "Big 5" group, and the other two are semi-large firms well-acknowledged for their technological achievements. The interactions were conducted entirely in Japanese between May and June 2022 and freely translated into this paper. The interviews were part of a broader study in which some questions focused on the *fukugōka kōhō* theme.

The participants belonged to various departments, including construction management, production technology, research and development, and design strategy. Their position varied from chief engineers to department managers and general managers. The average professional experience of the 14 participants was 30.75 years, with an average of 13.25 years on the gemba.

Table 2: Profile of the interviewees

Focus group	Interviewees: Position (Department)
Company A 2022.05.10	A1: Head manager (Building construction)
	A2: Head manager (Technical research institute)
	A3: Deputy manager (Operations support division)
Company B 2022.05.11	B1: Deputy director general (Building construction headquarters)
	B2: Manager, structure field (Production technology)
	B2: Manager, construction field (Production technology)
Company C 2022.05.12	C1: Head manager (Building construction)
	C2: Manager in charge (Building construction)
Company D 2022.05.27	D1: Head manager (Building technology)
	D2: Head manager (Building design strategy)
	D3: Chief structural engineer (Building design strategy)
	D4: Chief architect (Building design strategy)
Company E 2022.06.20	E1: Executive manager (Building construction headquarters)
	E2: Deputy general manager (Building construction headquarters)

FINDINGS OF THE HISTORICAL REVIEW

THE RISE OF FUKUGŌKA KŌHŌ

The Japanese construction sector has long faced a chronic labour shortage and declining productivity associated with an ageing workforce. Construction firms had struggled to find skilled tradespeople, mainly formwork carpenters and rod busters. At the same time, a plethora of new industrialised technologies was under development to meet ever-challenging project requirements, making construction methods more diverse and complex (Eguchi et al., 1988).

Despite the success of prefabrication among housemakers, production conditions were significantly different for order-made projects commissioned in mainstream construction. Traditional builders faced adversities associated with the uncertainty of the site environment and temporary supply organisations, making the production task more challenging. Still, general contractors were optimistic about off-site construction and positively invested in prefabrication technology development as part of rationalisation efforts (Takada, 1997).

However, precast concrete technology could not eliminate on-site operations because the joints still required local manual work (Konishi et al., 1996). Also, quality issues caused by flawed engineered interfaces disturbed users and urged hard-to-solve responses. Hence, *zairai kōhō*, considered more reliable, had to share the stage with prefabricated parts.

Ultimately, *fukugōka kōhō* served as an alternative to "pure prefabrication". It tackled issues left unsolved by the latter regarding productivity, quality, and its associated building performance, which were hard to perfect due to their production specificities. It enabled the realisation of superior structural performance and gemba productivity improvement by combining construction methods according to specific site conditions (Furusaka, 2009).

Figure 1 illustrates two examples of *fukugōka kōhō*. They shared the idea of utilising prefabricated components wherever possible and half-prefabricated parts wherever judged necessary to bind structural sections. However, the design details of those components and joints considered the specific production strategy of each firm and were often patented.

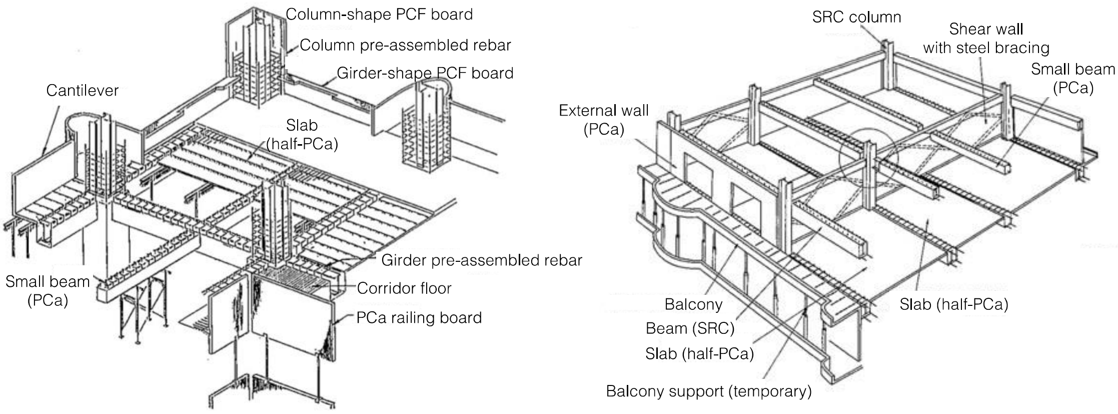

Figure 1: Examples of fukugōka kōhō (Adapted from: Sekō magazine, Aug 1986; Oct 1988)

The compounding approach enabled "leaner" sites to deliver buildings with similar outlooks, reducing wasteful local work subject to variability by systematically prefabricating components within reasonable boundaries, not pushing too much. Inspiration from the naval sector (i.e., Block Production System) and automotive sector (i.e., Just-in-Time) helped eliminate waste, overburden, and unevenness, the so-called *muda*, *muri*, and *mura* (Umehara et al., 1995).

By outsourcing tasks in the critical path, the project team could shorten the delivery time, reduce on-site personnel, and flexibly tighten connectors due to the modular design and the well-coordinated delivery of semi-finished parts, which were usually large and, in some cases, self-supporting. Consequently, the site necessitated fewer temporary construction equipment that obstructed the flow of people and hindered the execution of concurrent services.

DEFINITION AND TERMINOLOGY

Despite the absence of a resolute definition of *fukugōka kōhō*, the quote below hints on the concept development.

> "Fukugōka kōhō is a construction method that incorporates as many precast concrete (PCa) elements as possible into the skeleton constituent parts of a conventional structure (viz., generic cast-in-place concrete) aiming to improve the production efficiency on-site (Ueno et al., 1989)."

The terminology has changed as the management implications became clear. Records in the *Sekō* magazine revealed that the technology was first referred to as "*fukugōka kōhō*" in which the "*kō*" of "*kōhō*" was written with the ideogram "*takumi*" conveying a nuance of "engineering process (how to make it)". Afterwards, practitioners substituted that ideogram for "*kamai*", which is also read "*kō*" but suggests "structural composition (what is it made of)". Then, both ideograms were combined in a single word (*kōkōhō*) which implied that technologies were stacked together like a mosaic, integrating materials, equipment, workforce, and operations with the construction zone division and temporary work plans (Yashiro et al., 1993).

Regarding the specific names, it was common to attach a prefix (usually an acronym) that identified the core technology involved in each building system. Most companies labelled each variation by describing the specific material in use, functional cross-sections, connection types, and the target building typology to which it was conceived. Other companies would collectively address their inventions under an umbrella title, such as "*x-company-style fukugōka kōhō*".

PIONEERING SOLUTIONS

The planning of *fukugōka kōhō* resulted from the iteration of construction method selection and combination for rationalisation purposes. Construction firms first prioritised structural systems over other disciplines, considering it would bring impact benefits to urgent issues, such as cost. Despite the technical challenges, contractors believed that accumulating improvements over time would make these composite structures more robust and reliable (Eguchi et al., 1988).

Figure 2 illustrates the construction cycle of a project employing *fukugōka kōhō*, which directly impacted work structuring. The mix of precast and conventional work set specific takt times that were usually in between those estimated to *zairai kōhō* and full prefabrication.

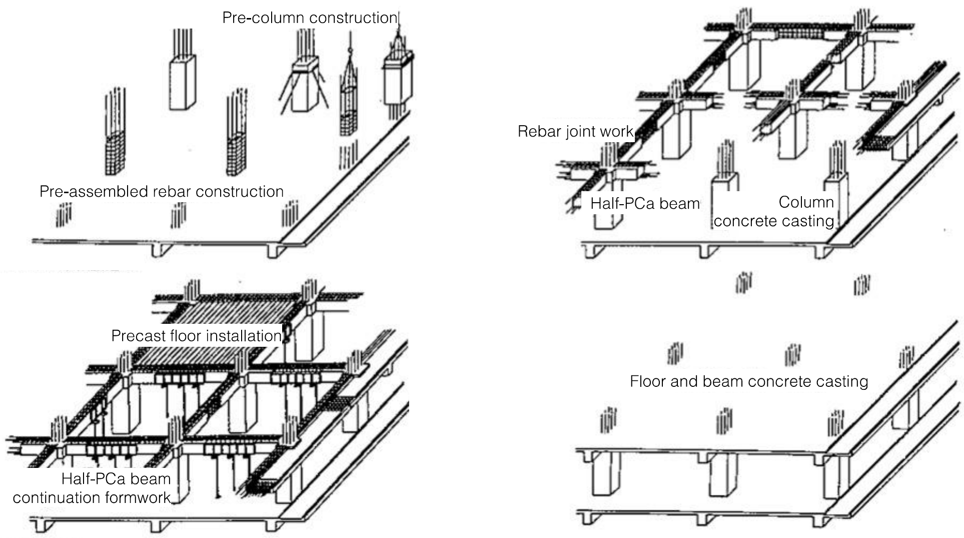

Figure 2: Construction cycle with fukugōka kōhō (Adapted from: Sekō magazine, Jan 1991)

A survey by Konishi et al. (1996) with several companies identified the most recurrent merits among 51 composite construction method variations. A breakdown of these factors revealed that the leading one was time shortening (43), followed by labour-saving (*shōryokuka*) (38), quality improvement (29), personnel reduction (*shōjinka*) (28), proficiency effect (*shūjuku kōka*) (27), cost reduction (26), and material-saving (24). Other benefits reported included the independence of weather conditions, the possibility of constructing higher buildings, larger spans, lighter structures, and improved earthquake resistance, to name a few.

A major consequence of *fukugōka kōhō* was the simplification of temporary construction (*kasetsu kōji*). The reduction of storage, transport, and safety installations implied cost savings and clear space for the remaining work on-site. For instance, precast horizontal boards avoided vertical supports and allowed the quick start of subsequent tasks. Parallel work optimised equipment utilisation (*kadōritsu*) and promoted site tidiness (viz., 5S workplace organisation).

A study by Ueno et al. (1989) compared two projects of similar scope and scale (3-story residential building) in which one employed *zairai kōhō* and the other *fukugōka kōhō*. Regarding resource utilisation, the project with *fukugōka kōhō* saved about 30% of man/hour in the structural frame construction and about 30~50% in the formwork, rebar, and concrete casting operations. The cycle process was shortened from 12 to 8 days, and the total construction time was compressed from 15 to 12 months.

INTERVIEW RESPONSE-BASED CONSIDERATIONS

DRIVERS AND BARRIERS IN ADOPTING FUKUGŌKA KŌHŌ

The historical survey revealed that the **main drivers** for adopting composite construction methods in the so-called first-generation *fukugōka kōhō* (1970-1990) were:

- Productivity (or QCDSE in the broadest sense).
- Structural performance (or overall building performance).
- Flexibility of construction process and operations.
- Product individualisation and customisation capabilities.
- Enhanced component supply and on-site logistics.

The interviewees were asked about the main reasons for adopting composite construction methods today in light of the current industry situation. The motivation has not significantly changed, as the most frequent responses were pursuing "*cost reduction*" through the willingness to increase productivity compared to conventional construction methods.

> "It is [mostly] about money. The selection of construction methods considers the customer's requirements. Roughly speaking, decision-making strives to balance cost and construction time. [That is because] there are cases where they are willing to pay a bit more for faster construction (Mr A1)".

The secondary factor was the "*flexibility*" of the construction process and operations. The argument was supplying the advantages that an element technology is good in a composite structural system that better fits the project overall. The other factors were pointed out as "manageable". Although not necessarily easy to solve, the engineers "don't overthink them". Regarding *structural performance*, the interviewees reported that improved material properties (viz., high-strength concrete) have made combining too many different materials unnecessary to extract their advantages (e.g., employing RC where SRC used to be required), making the construction process simpler and more efficient. By all means, the application was contingent on compliance with technology evaluations and obtaining permission from the local authorities.

> "I think structure performance was not a reason to adopt *fukugōka kōhō* because the selection of a construction method must ensure '*dōyūi tanpo*', that is, the new candidate must ensure equal advantage or performance superiority compared to established methods (Mr B2)".

In the past, the construction method combinations were necessary for erecting a building with particular architectural features (i.e., high-rise, large spans, earthquake resistance). Now, many venturous designs are possible with fewer structural type combinations which means a trend toward simplification. Structures of either "single-type method" or "composite method" must satisfy the design's performance specifications and adhere to technical requirements.

Construction records of the historical survey revealed that the **main barriers** to deploying the first-generation *fukugōka kōhō* (1970-1990) were:

- The need for adaptation and rework due to the complexity of the design.
- Lack of skilled labour.
- Technology interface issues.
- Regulatory permissions (i.e., technical standards, town planning etc.).
- Reliability of parts and component supply.

The discussion about the barriers called out the kernel of the composite construction method idea. Some interviewees highlighted that *fukugōka kōhō* variations were devised to overcome the pitfalls of previous construction methods, so it was hard to point out their barriers.

> "Generally speaking, *zairai kōhō* is the reference construction method to be employed. Occasionally, we face a problem such as 'the construction period is too short' so the adoption of *fukugōka kōhō* is worthwhile. Regarding the barriers, I would say that solving the decomposition and continuity between construction methods is challenging (i.e., *technology interface issues*) (Mr A1)".

Furthermore, *fukugōka kōhō* can simultaneously raise advantages and disadvantages on the same factor. For instance, 'cost-saving' was considered the main reason for adopting. However, the extra cost of adapting the technology to peculiar project conditions (rework of designing a piece devised for a different construction method) can be a barrier at the same time.

> "In principle, *fukugōka kōhō* takes only the good parts of each element method, so adding a few PCa in *zairai kōhō* structures would be good. However, off-site production implies the need for transportation, which implies extra costs (Mr C2)".

Some of the obstacles of *fukugōka kōhō* are similar to those of *kōgyōka kōhō* (prefabrication) since the latter is integral to it. The external and internal logistics are a case in point.

> "A significant factor is the yard condition. Whether there is a yard or not, whether a crane can be placed or not, whether the trucks can come in or not (Mr B3)".

Because *fukugōka kōhō* was new to most players, project teams struggled to understand the underlying process and streamline actions leading to tangible gains. The information flow and decision-making chain could fall short of clarity when adopting novel arrangements.

> "If we adopt a generic (default) construction method, there is a generic flow to proceed. However, *fukugōka kōhō* does not follow the generic flow. So, we must imagine and elaborate it (from scratch) by ourselves (Mr A3)".

Moreover, the new combination must meet the quality and performance threshold; otherwise, it will be rejected as a candidate system for that project.

> "If it clears the quality threshold, we will check the cost merit. After that, we assess the impact in construction time. […] We want to select a combination that takes this balance. We often ask ourselves: 'How far should we prefabricate?' (Mr D1)".

The need for adaptations in the construction plan and the rework of interface design undermined a more extensive application. Thus, design-bid-build projects in which the design comes from an external office were also more challenging to deal with than design and build commissions for a single firm (large Japanese general contractors hold full-scale design teams).

TECHNOLOGY ADVANCEMENT AND CHANGES IN ITS IMPORTANCE PERCEPTION

Regarding the **conceptual and physical changes** over the decades, it was unanimous that progress in building materials promoted significant transformations in structural design. These changes modified the strategies for the appointment of corresponding construction methods.

> "In the 1980s, PCa was widely discussed. However, at that time, there was no high-strength concrete as we have today, so it would have been impossible to build high-rise buildings only with PCa (Mr A1)".

An example was the substitution of SRC by PCa frames for high-rise building structures, thanks to the evolution of concrete technologies, reducing gemba operation complexity.

> "About 40 years ago, SRC was the only choice for high-rise residential buildings because of its superior performance. However, SRC is expensive and makes the construction period longer. From the 1980s, [high strength] PCa became an option. Nowadays, there are almost no new buildings with SRC (Mr B1)".

Fukugōka kōhō aggregated PCa parts into conventional RC skeletons for rationalising the erection process. It also combined RC columns and S beams to extract their superior structural properties, creating many design variation possibilities to satisfy customer needs.

> "In the 2000s, we often used a construction method of RC columns and S beams. It was a way of having the best of each material. The older mentality was 'If I use an S beam, then I should use an S (or SRC) column too'. However, the development of joints has made it possible to use this (alternative) combination (Mr B2)".

Because the number of prefabricated parts increased, construction equipment had to become more efficient. Consequently, scheduling and stock management adapted to the new erection pace. However, the productivity of people-operated tasks has not changed much since then.

> "The capacity of tower cranes has increased. In the past, they lifted no more than 20t. Also, the provisional service elevators have become faster (Mr C1)".

It is worth noting that the term *fukugōka kōhō* became unused over time. There is an awareness that undertaking 100% *kōgyōka kōhō* (prefabrication), although not impossible, is complicated and not necessarily worthy depending on the project conditions.

> "I think the so-called *fukugōka kōhō* that flourished in the 1990s has provided good combinations of element construction methods. However, the technology was still in its infancy at that time. […] In our company, we have developed a comprehensive construction method called '*x-construction method*' (pseudonym). Since then, we probably have not called it *fukugōka kōhō* anymore (Mr A1)".

Similarly, in the idea, but without a standardised solution pattern, some companies referred to their subsequent *fukugōka kōhō*-ish arrangements as a "hybrid construction method" or merely a "rationalised construction method".

> "PCa (prefabrication) is the choice with the highest merit. However, the cost factor recurrently leads to hybrid options with *zairai kōhō*. The construction time might enlarge a little (compared to pure PCa). The so-called 'hybrid method' or 'rationalised method' takes the balance of cost and time (Mr E2)".

The theoretical concept of *fukugōka kōhō* was not uncontroversial and is hardly mentioned today. Young architects and contractors face the term as a simple description of an engineering strategy rather than an actual concept. The interviewees reacted with surprise when asked about their memories and reflected on how they could be helpful today. Besides, they demonstrated a certain nostalgia and conjectured that "almost everything today is a sort of *fukugōka kōhō*". They would not spend much energy on it because "it just sounds natural" to pursue prefabrication without "doing *muri*" and relying on *zairai kōhō* when inevitable.

DISCUSSION: DIRECTIONS FOR NEW BUILDING SYSTEMS

The compounding approach had taken part in construction rationalisation policies (*gōrika hōshin*) initially emphasising productivity and quality (Takada, 1999). Despite not using the word "lean" explicitly, many "*gōrika"* efforts resembled what the West would call lean-ish endeavours, pursuing eliminating waste and improving flow. *Fukugōka kōhō*, within that macro-concept, could be considered an unconscious and partial "lean construction" example.

Regarding the lessons to devise future construction systems, there was no consensus on whether the proportion of prefabrication shall increase, decrease, or continue at about the same level as today. It would depend on whether construction robotics will make local operations more advantageous than bringing on semi-ready parts. Ultimately, "new hybrid" construction systems could result from sophisticated prefabrication and on-site automation coordination. For the automation element, the *Construction RX Consortium* (2023) is an example of technology cooperation aiming at labour saving and worksite efficiency through site robots introduction in gradual steps. The initiative does not claim to be lean but features some lean-ish characteristics.

The interviewees suggested that a new *fukugōka kōhō* employing on-site robotics could be developed shortly, but probably without using the "composite construction method" name.

> "The changes are from hereon. Digital technologies have evolved a lot. However, the fundamental aspects of the production systems have not changed yet. There is progress in elemental technologies. Now, we are investigating 'how to link these element technologies to our productivity improvement actions' (Mr B2)".

The development of *fukugōka kōhō* had been partially *cumulative* on a succession of routine improvements (*kaizen*) and *disruptive* as part of innovation programs to anticipate response to social and market change. Compared to the robotics wave of 30-40 years ago, there is an increased willingness to employ assist robots. They are not meant to replace humans but aid the fewer (multi-skilled) of them who remain on-site to perform as much as many workers traditionally, reducing redundancy (waste). Still, systematic robotic utilisation shall satisfy certain conditions, including finding the necessary input to start operating. However, these robots still do not hold enough autonomy to handle "improvisations" and deal with their risks. The word "making-do", as defined by Koskela (2004), is not heard in Japanese gemba, but a similar "drive" or "impulse" to control them tacitly exists in *dandori* arrangements.

CONCLUSION

The labour shortage issue has been further aggravated in Japan and other countries. In response, construction firms have proactively set internal policies to promote off-site production. Nevertheless, they have been conservative about the time robots developed in the R&D laboratories will run in the real gemba. The lessons of the past showed that the hurdles of "full prefabrication" and "full automation" are exceedingly high. Thus, it has been more realistic to face automation as performing an "assist" function, and prefabrication as a spotted strategy.

Former versions of *fukugōka kōhō* brought out the best of "off-site and on-site" for optimal efficiency with a touch of parsimony. Future building systems are likely to follow the compounding rationale. However, the "on-site" part might be modified due to recent technologies. The "*new fukugōka kōhō*" will likely be a mix of "off-site/on-site" in which the on-site work will be more digitalised, contingent on technology robustness issues.

Since new combinations are subject to falling short in performance-quality trustworthiness (trial-and-error experimental nature), the transition will take time. The deployment of "*new fukugōka kōhō*" depends on the construction method technology in itself but also the ability of design teams to devise coherent and robust combinations in response to the project requirements. Procurement models integrating design and construction control (*sekkei-sekō*) provide a favourable ground to maximise the available machine's capabilities and realise frontloading.

Lastly, stakeholders must beware of the advantages and limitations of each elemental technology and communicate with construction planners and component suppliers to streamline the comprehensive production system. Therefore, the realisation of such building system design is the product of sophisticated internal and external teamwork pursuing the balance between optimal and feasible. It is, ultimately, a tacit expression of lean-like efforts. It may be a peculiarity of the Japanese construction industry and business environment and not necessarily applicable to projects where the underlying conditions are significantly different.

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EXPLORING A PLATFORM APPROACH TO IMPROVE THE UPTAKE OF OFFSITE CONSTRUCTION IN HOUSEBUILDING: EVIDENCE FROM THE UNITED KINGDOM

Zoe A. Kennedy[1], Emmanuel I. Daniel[2], Matthew Egan[3], Trudi Sully[4], and Gaynor Tennant[5]

ABSTRACT
The purpose of this this research is to create guidance and direction for industry especially developers and / or housebuilders who can directly influence the decision-making process to create buildings and land developments that are considered more valuable. The UK has a massive housing shortage and with the added pressure of climate change and a very fragmented construction industry the need to look at smarter building methods is critical. The benefits of offsite construction are well documented but still thought of as expensive and high risk, therefore other solutions such as platforms could lower the barrier of entry and increase uptake. This study aims to investigate the current understanding of platform construction and the challenges that are contributing to its slow uptake. Qualitative research method was used and only construction professionals who have experience in offsite construction were interviewed to ensure the richest information. The study found that cost and supply are the core issues limiting uptake of product platforms. Through the continuation of government and industry collaboration, both supply and demand can be aggregated to solve these issues. However, the bar for improving knowledge and understanding across industry needs to be raised and points of recommendation are provided.

KEYWORDS
Offsite construction, product platforms, manufactured construction, standardisation, collaboration

INTRODUCTION
To date, the UK construction industry has been built on inefficient processes and often described as a broken business model with issues relating to construction costs, supply, labour availability, productivity, and fragmentation in the market (Egan, 1998; Farmer, 2016). Many countries are facing a housing shortage and the UK is no different with projections of the

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number of households in England rising from 23.2 million in 2018 to 26.9 million in 2043 (House of Commons, 2021), which means the sector desperately needs to create more high quality and sustainable housing. With the construction industry contributing to 39% of global carbon emissions (WBCSD, 2021) it means the sector must also change the way it designs and builds to mitigate the acceleration of global warming. Looking at smarter ways to build, through manufactured construction, will not only help both the UK's housing shortage but also help decarbonise the sector.

Offsite construction has a critical role to play in moving the industry forward, however, to date the uptake of offsite manufacturing approaches remains low within UK housebuilding (MGCLG, 2019; Marte Gomez et. al., 2021). Offsite construction techniques where entire modules are constructed in a factory need extremely high capital costs for investment and funding. For one, there is a huge investment for the factory setup alone, plus with factory production there are very high upfront costs for production and delivery to site (Goulding and Rahimian, 2019; Barbour ABU, 2020; Tuesta et. al., 2022). As per, House of Lords, 2018, this means a lot of working capital is tied up, especially if the manufacturer is not paid until work is delivered to site, and that can be very challenging in terms of cash flow for the manufacturer to stay afloat. In fact, that can be the difference between an offsite manufacturer being successful or not as the case maybe. Platform construction, as per Mosca et. al., 2020; CIH, 2022, comprise of standardised interoperable components and assemblies which can be used at scale as well as standardising processes and programmes which ultimately will reduce project cost, delivery time and carbon emissions. A platform approach also creates a lower barrier of entry around investment and risk that come with offsite modular construction (Barbour ABI, 2020).

In an interview conducted by Bryden Wood, a manufacturing design and engineering practice, it highlighted there is a mindset shift is needed to really progress the uptake of manufactured construction by making better choices early in the process. This means that smaller housebuilders and developers have a pivotal role to play to ensure a better delivery of housing stock (Bryden Wood, 2021). This research tests the viability of manufactured construction, such as offsite and platform approaches, amongst UK housebuilders and developers by encouraging "manufacturing thinking" right at the very start of a project to drive design, client and supply chain engagement (Goulding and Rahimian, 2019; Tuesta et. al., 2022). To improve uptake of offsite construction and increase the housing supply in the UK this study seeks to achieve these two objectives:

1. Investigate the current level of knowledge amongst UK developers and / or builders, concerning platform construction;
2. Identify the challenges that prevent UK developers and / or builders from adopting such building methods thus contributing to the slow uptake of offsite construction.

LITERATURE REVIEW

OFFSITE AND PLATFORM CONSTRUCTION

Offsite construction typically has become to be known as an approach to a project whereby a proportion of construction activities are carried out under factory conditions and then later transported to the site usually in the form of complete modules (Goulding and Rahimian, 2019; CITA, 2022). It has been recommended as part of the solution to solving some of the inefficiencies in the construction sector for decades now from the UK's government report Re-thinking Construction (Egan, 1998) to the government's review of the construction labour model in Mark Farmer's Modernise or Die report (Farmer, 2016). Subsequently this has evolved thinking and best practices by taking the learnings from other manufacturing industries, like automotive, and applying them to the delivery of buildings. The construction sector is now using terms such as 'standardisation', 'lean manufacturing', 'pre-assembly', 'economies of scale' which has given rise to various categorisations of offsite construction designed to help improve understanding and confidence in the use of smarter building techniques (MHCLG, 2019).

Figure 1 was developed for a report for Construction Research & Innovation Strategy Panel (CRISP) and focuses on the term 'pre-assembly' by subdividing into four categories based on increasing amounts of pre-assembly (Gibb and Isack, 2003). More recently, in Figure 2, construction was further defined by incorporating innovative construction techniques known as the Modern Methods of Construction (MMC) Definition Framework (MHCLG, 2019). This divided the innovative construction techniques or MMC into seven categories by encompassing a range of offsite manufacturing and onsite techniques and measuring how much pre-manufacture is used on a construction project. Measuring pre-manufacture or Pre-manufactured Value (PMV %) enables organisations to adapt design, supply chain and construction choices to aggregate and standardise demand (Pan and et. al., 2008; MHCLG, 2019).

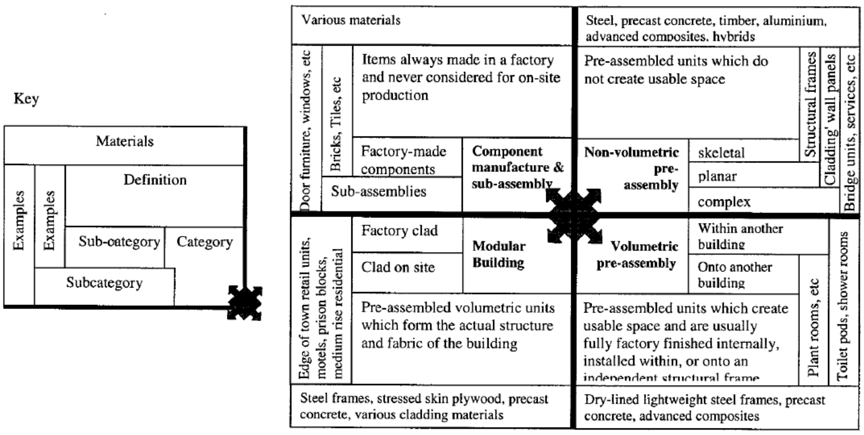

Figure 1: Four categories of pre-assembly, definitions, subcategories, examples and main materials (Gibb and Isack, 2003)

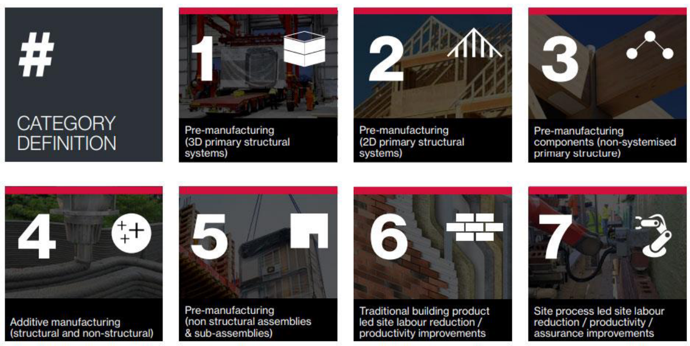

Figure 2: The MMC Definition Framework: Categorisation (MHCLG, 2019)

Platform construction, however looks at the project holistically by identifying commonalities and creating components that offer a higher level of standardisation and repetition (Barbour ABI, 2020; CIH, 2022). This negates the need for a large costly factory because platforms can leverage on existing processes through value engineering and continual improvements (Bryden Wood, 2021c; Bryden Wood, 2018; Barbour ABI, 2020). As per Mosca et. al., 2019, there are many kinds of product platforms but they all have three characteristics. Firstly, a group of fundamental components, such as a car's chassis, that don't vary too much. Second, a group of auxiliary parts which may be paired with the chassis to produce lots of repetition of the same vehicle. And lastly, a reliable interface that enables the components to connect (Mosca et. al., 2020; CIH, 2022). So whichever framework is used to categorise offsite manufacture, whether it be Figure 1 or Figure 2 or another, they illustrate examples of pre-assembly or pre-manufacture in construction, which really aligns to the thinking of a product platform approach by providing a stable core which is configured and combined with complementary components (via defined interfaces) to suit a particular project (CIH, 2022).

MANUFACTURED CONSTRUCTION PRINCIPLES

In understanding offsite and platform construction techniques and securing the benefits of these manufacturing led processes in housebuilding, there is a real need to recognise the importance that "manufacturing thinking" is different to "construction thinking". As per Bryden Wood, 2021c; Bryden Wood, 2018; Goulding and Rahimian, 2019; Tuesta et. al., 2022, a key manufacturing principle is to strip out anything that is non-value adding and work out what is the leanest possible way to deliver it to the end user. Design for Manufacturing & Assembly (DfMA) describes the process of manufacturing and assembling a product and the need to design a product towards the process (Bryden Wood, 2021).

One of the major problems in the construction industry is that far too often people do a traditional design process and then shoehorn DfMA into a project such as modular or panelised. This compromises the design by making it fit the system and thus designing an inefficient system. This is where architectural and consultancy practices specialising in offsite construction would be able to add significant value in the process by being system-agnostic and designing the best solution for that project also advocating the role of the MMC Adviser at RIBA Stage 0 (Modularize, 2021; RIBA 2021). In manufacturing there is a different set of constraints to traditional construction such as manufacture and assembly (and dis-assembly), transport, safety, cost, environment etc. which all need to be carefully planned and considered right at the very start of a project (Modularize, 2021; Laovisutthichai et. al., 2022; CITA, 2022).

According to Zhang and et. al., 2009, DfMA is more familiar in offsite construction such as building fully completed volumetric and modular buildings where there is controlled environments and optimised processes. Platform construction, takes components and assemblies that can be put together in lots of different ways to make lots of different products and has been termed a 'kit of parts' (Bryden Wood, 2021c; Bryden Wood, 2018).

Identifying commonalities to work from a common kit of parts and applying manufacturing techniques and processes can really drive productivity, innovation and cost efficiencies (Zhang and et. al., 2009; Barbour ABI, 2020). As mentioned, product platforms are used extensively in the automotive industry where there is a lot of customisation but use the same components and standard manufacturing processes, for example BMW and VW use the same chassis on a lot of their models and it's the engine, the wheels, the trim etc. that make the car different even though technically it is the same model allowing a degree of customisation (Bryden Wood, 2021).

PLATFORM CONSTRUCTION DRIVERS AND ENABLERS

The UK's government for procuring construction has changed significantly and has seen them championing MMC and committing to migrating from traditional construction techniques to smarter building methods. The creation of the Product Platform Rulebook was created to support the implementation of the government's strategies outlined in the Construction Playbook [December, 2020] to improve the uptake of MMC and increase adoption of platform approaches also described in TIP (Transforming Infrastructure Performance): Roadmap 2030 [September 2021] which builds on the Industrial Strategy of 2017 about delivering greater value in buildings (HM Gov, 2017; HM Gov, 2020; IPA, 2021; CIH, 2022). The Rulebook, therefore, not only sets out 'The Rules' that should be followed to develop a successful product platform but also details a common framework of approaches that can be used to implement a platform approach to delivery (CIH, 2022; Bryden Wood, 2021c).

The Platform programme therefore incorporates an end-to-end solution by re-evaluating the whole construction process, not just by considering the kit of parts approach and associated manufacturing processes but the knowledge, people and relationships required to deliver a project from inception to completion and beyond. It therefore focuses on 1) utilising manufacturing approaches to improve efficiencies by shifting focus to quality, performance and whole-life value; and 2) changing behaviours of clients and supply chain by enabling all-encompassing outcomes. This is really important as the industry moves towards a focus on performance outcomes and building a net zero carbon future (CN, 2021; Bryden Wood, 2021b).

RESEARCH METHOD

In order to look at a project more holistically so it can drive improvements by focusing on outcome-based specifications it needs to be pushed by industry. This puts emphasis on the housebuilding community to ensure a better delivery of housing stock by making decisions earlier on in the process (Bryden Wood, 2021). However, because the understanding of platforms is a relatively a new subject, a qualitative approach was used for this research to allow a more thorough discovery into this subject area (Nauom, 2013; Fellows and Liu, 2015). To date the current information available on platform construction is based on offsite manufacturing philosophies and lean manufacturing practices to improve efficiency and eliminate waste (Laovisutthichai et. al., 2022; Goulding and Rahimian, 2019; Tuesta et. al., 2022). At scale these methodologies have successfully been adopted in other industries such as automotive but have not yet translated to the construction industry.

This means the numerical data is not readily obtainable for manufactured housing because it has not yet “stood the test of time” compared to traditional methods of construction. A lot of the information to date, therefore, remains idealistic and even though there has been some great work between government and industry showing the potential of manufactured and platform construction, it doesn’t show the scale it needs to become mainstream (CIH, 2022; Bryden Wood, 2021c). This new concept of platform construction means a purposive sampling technique was best suited for this research allowing people with the most knowledge to participate in order to ensure the richest information was obtained (Braun and Clarke, 2013). Because of the newness of ‘platform construction’ more recognised terms such as ‘volumetric’, ‘modular’, ‘panelised’ etc. were used to identify those that have used manufacturing techniques in their building practices. This was essential to ascertain if a platform approach could be adopted more widely to build more quality houses faster.

Structured interview questions allow more accurate answers to be obtained compared to unstructured ones, as well as helping the interviewer to remain impartial (Naoum, 2013). For this research a semi-structured approach was taken by using both open and closed questions to 1) help prevent predeterminism but 2) allow respondents to give their views and opinions where necessary (Naoum, 2013). During data analysis common language was identified, in the form of themes and sub-themes, to rationalise the results. Thematic analysis is an approach that determines a level of prevalence by using code-frequency counts to identify common patterns in the data (Braun and Clarke, 2006; Braun and Clarke, 2013). Therefore, a middle-ground was achieved through the inclusion and exclusion of code-frequency counts.

RESULTS AND DISCUSSION

RESPONDENTS BACKGROUND

Although some additional dialogue with industry experts was undertaken to allow a deeper examination of this subject area, the focus of this research methodology is the UK housebuilding community. Therefore, twenty developers and / or housebuilders and key personnel were identified and contacted based on their knowledge and experience in this field of study, with ten confirming their participation. Before any data collection was undertaken respondents were asked to confirm their business category e.g., builder, developer or developer-builder and the type of housing projects they are involved in e.g., build-to-sell, detached, low-rise, affordable etc. etc and confirm their understanding of platform construction.

RESPONDENTS UNDERSTANDING OF PLATFORM CONSTRUCTION

The research showed that most of the respondents, 90% in fact, had heard of the term platform construction shown in Table 1. But to evaluate the true understanding amongst respondents they were also asked to describe platform construction which as in seen in Table 2 comprises of three initial codes. What this shows was most respondents mentioned the Use of a manufactured construction process to create efficiencies in the build by standardising components like they do in the car industry; using the same components & standard manufacturing processes to build, offering different finishes & ways to assemble to create variation, in the words of one respondent, "Constructing buildings in a manufacturing way – not just efficiencies in the design & build of the product but also in the process."

Table 1: Data analysis of respondents re. What is platform construction?

S. No	Description	Frequency	Percentage
1	Yes	9	90%
2	No	1	10%
Grand Total		**10**	**100%**

Table 2: Detailed data analysis of respondents re. Understanding about platform construction

Themes	Initial Codes	Frequency	Quotes from Transcripts
Understanding about platform construction	Building with a manufacturing mindset	1	Building with a manufacturing mindset by limiting choice to leverage greater economies of scale.
	Standardising	2	The ability to standardise the main asset like a chassis of a car and then a continuous reuse of manufactured components to produce variations in the supply chain. For example, VW Beetle and VW Golf are the same chassis! Kit of parts approach creating standardised components, with standardised processes to create efficiencies whilst having customisation.

Use of manufactured construction process	5	Using manufactured construction processes to create efficiencies in the build by standardising components like they do in the car industry. Using the same components & standard manufacturing processes to build, offering different finishes & ways to assemble to create variation - car industry!! Constructing under the limitations of manufacturing techniques to produce very efficient buildings. Using a manufacturing environment to create a fixed set of parts that can be put together in different ways to create variety & throughput. Constructing buildings in a manufacturing way - not just efficiencies in the design & build of the product but also in the process.

During the launch of the new DfMA Overlay to the RIBA Plan of Work, one of the major challenges that has contributed to the slow uptake of MMC and DfMA is a fundamental lack of understanding within the construction industry about manufacturing processes (RIBA, 2021; SCSS, 2021). Because there are currently so many variations and interpretations around terminology, whether it be modular, offsite or platforms, it makes it a very confusing and complicated landscape to work in (RIBA, 2021). Most of the respondents interviewed used these terms interchangeably to mean the same thing including modular, DfMA, MMC, offsite, prefabrication. Certainly, some respondent's understanding was more comprehensive than others, but most could relate platforms to manufacturing processes such as the automotive industry and understood the need to standardise to create efficiencies in the construction process.

But this confusion around terminology therefore limits the respondents understanding about how to get the best out of manufactured construction. As per Modularize, 2021; SCSS,2021, it was discussed that offsite architects that work across all MMC systems can identify the best solution for that project, therefore not limiting the design to a particular system. This coupled with the role of the MMC Adviser to be assembled as part of the project team at RIBA Stage 0 will ensure that offsite is not an afterthought, so all the benefits of MMC can be consumed and it does not impinge on design choices and customisation (RIBA, 2021). Although standardisation creates less design and layout choice compared to traditional, there are still lots of opportunity to create customisation by offering a variety of sizes, materials and finishes to suit different tastes, styles, and types. As per Mosca et. al., 2020, platforms need a holistic approach to be successfully adopted therefore moving the conversation away from cost and focusing on performance outcomes.

THE CHALLENGES SLOWING MMC UPTAKE AS PER THE RESPONDENTS

To identify the challenges that prevent UK developers and / or builders from adopting manufacturing techniques, respondents were asked to give their key reasons for the slow uptake of MMC allowing four initial codes to be formed as highlighted in Table 3.

Table 3: Detailed data analysis of respondents re. Key reasons for the slow uptake of MMC

Themes	Initial Codes	Frequency	Quotes from Transcripts
Key reasons for the slow uptake of offsite construction	Cost related issues	6	No cost benefits. For most projects we undertake it's not cost-effective compared to traditional. We are a developer / builder that sell our houses, so cost is a major driver. Ultimately we can talk about other value drivers such as innovation and sustainability but if you can't make the project viable it becomes irrelevant. The build size cost is too high for offsite, of course if you can build in volume and benefit from economies of scale it is cost comparable. But most brown field sites don't offer the opportunity to build 100 homes at a time. We've looked at modular several times on larger projects & still unable to get the numbers to stack up in terms of viability.
	Other	1	Planning is inadequate – lots of challenges here but main issue is that current planning policy does not consider zero carbon. MMC houses surpass building regulations but there is no recognition of that in current planning policies – you still only need to meet building regs.
	Lack of Understanding	2	Lack of understanding in how to deliver MMC therefore no cost benefits. Too late post-planning
	Supply Chain Issues	5	No cost certainty from supply chain. Not enough supply-chain availability and no interoperability. Not enough supply chain capability on the market. Manufacturers not interested in small projects – need volume. We build high-end luxury homes – at the moment there isn't enough design flexibility in the current supply-chain without incurring huge cost.

Cost was definitely a bone of contention throughout the interviews, in the words of one respondent "Ultimately, we can talk about other value drivers such as innovation and sustainability but if you can't make the project viable it becomes irrelevant"." A lot of this can be attributed to the lack of understanding in the level of detail required at the early design stages of a project as discussed in the above section (Modularize, 2021; CITA, 2022). In manufacturing there are a different set of constraints to be considered right at the very start of a project compared to traditional construction and it is knowing these intricacies that will give housebuilders and developers the edge to maximise project value and deliver a viable and cost-effective solution (Modularize, 2021; CITA,2022). Also, it brings into focus about not looking at a project in isolation and designing bespoke every time like traditional construction. Of course, a platform approach makes sense when delivered at large scale but even for small housebuilders there's no reason why some elements and processes cannot be standardised and used across multiple sites to reduce costs (Bryden Wood, 2021a; (CIH, 2022).

An interesting finding in the research contributing to the slow uptake is the planning inadequacy with one respondent making the point "Planning is inadequate – lots of challenges here but main issue is that current planning policy does not consider zero carbon. MMC houses surpass building regulations but there is no recognition of that in current planning policies – you still only need to meet building regs." If industry were able to get to a point where it was evaluating on other aspects such as social, economic, or environmental outcomes, it could then start to bridge the gap between on-site, offsite and everything in between. This might even remove the confusing industry terminologies and rather than differentiating between offsite and traditional, it could be referred to as just 'construction'. The use of materials are the same whether you build on-site or offsite, it's just the location that changes to whether it is built in a factory or on-site. As per CITA, 2022; Daniel et. al., 2020, most house designs surpass building regulations as standard in terms of airtightness and thermal performance, but if there is no recognition of this in current planning policy these extra costs a 'green' developer incurs naturally make offsite construction more expensive compared to traditional.

One of the other recognised challenges amongst the respondents was the insufficient supply-chain with one respondent saying there is "Not enough supply-chain availability and no interoperability". The result of this is the developers and / or builders interviewed felt the current supply-chain is monopolising the marketplace making a manufacturing option unviable in terms of price competitiveness (compared to traditional). And because every manufacturer is doing something slightly different, there is no interoperability, so each time a project must be redesigned as per the manufacturers system (Modularize, 2021; Bryden Wood, 2021a). As mentioned, where platform construction starts to be viable is delivering on large scale to drive the benefits of applying the standardisation of process and approach (CIH, 2022). But if there was interoperability and willingness to collaborate in the industry, it would allow manufacturers to come together and deliver a much larger programme (Daniel et. al., 2020). For example, by having different manufacturers using common elements, and potentially being able to procure together, not only is it a much more exciting environment in terms of materials, appearances, and styles, it becomes a much stronger commercial case for them to be involved. But as one respondent went onto describe so much of this is chicken and egg because for the supply chain to work together and invest, they need to have confidence in demand. That's the problem to date that so many of the platform projects highlight the opportunity but not the scale (Bryden Wood, 2021a; Bryden Wood, 2021b; Bryden Wood, 2021c; CIH, 2022).

CONCLUSIONS AND RECOMMENDATIONS

The aim of this study is to improve adoption of offsite construction, by investigating if a product platform approach can lower the barrier of entry and scale housing production in the UK. The study found that lack of knowledge of the platform approach, lack of supply chain capability and cost are among the barriers to the adoption of the platform approach. The study also found that the current planning policy that do not fully incorporate NetZero carbon limit the level of adoption of the MMC by house builders. For sure, there are a lot of challenges to overcome, but it is this joined up approach with government and industry working together that will move the industry away from procuring on just cost. This enable higher quality and sustainable houses to be built faster. As seen the Platform Rulebook has been instrumental in setting out key processes and approaches to enable the market to develop product platforms and learn how to deliver platform projects at scale.

Although the industry may not be quite there yet, as this research was conducted, the elements are coming together, and this makes the industry a very exciting place to be right now. As the industry moves away from cost to performance outcomes it will start to create an equal playing field for construction. Digitalisation of course will support this transformation and expanding interoperability to technology will allow the design process to be sped up to facilitate true digital design and operation. However, it cannot be stressed enough the industry needs to collaborate to innovate and make the industry less complex and more efficient to work in. Those three words from the Construction Playbook 'harmonising', 'digitising' and 'rationalising' demand will enable standardised and repeatable components and interfaces to be designed and drive the adoption of offsite manufacturing technologies.

RECOMMENDATIONS FOR INDUSTRY

This study helps anyone working in the UK residential sector by improving industry knowledge and understanding. It is joining up the design, client, and supply chain relationships to work in collaboration, that will assist UK developers and / or housebuilders in making manufactured and platform construction their first choice. The main points of recommendation are:-

- Manufactured construction is not an afterthought, it is a conscience business decision that is made at the start of a project with buy-in from all the project stakeholders;
- Understand that a manufacturing approach has a different set of constraints to traditional construction and therefore cannot be procured in the same way;
- Look at the project more holistically and move away from cost by focusing on performance outcomes and building a net zero carbon future;
- Standardising, components, assemblies and processes, as much as possible and taking the concepts and learnings across multiple projects will reduce costs in the long run as well as strengthening supply and demand;
- To unlock the true benefits of DfMA engage early with a MMC Adviser / Specialist Offsite Architect (ideally RIBA Stage 0).

This study is limited to ten interviews which may not adequately present the state of the art of application of the Platform approach in the UK. Future study should conduct an industry wide survey to present a more broader picture of the issue. Case study approach should also be used.

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APPLICATION OF FUZZY LOGIC FOR SELECTION OF OFF-SITE CONSTRUCTION APPROACH

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ABSTRACT

Compared to other industries, the construction sector has poor productivity performance. Many megaprojects in this industry incur cost overruns, and this is largely due to inefficiencies. Although there are several reasons for these inefficiencies, the most significant factor is the lack of efficiency. One effective solution to improve productivity in construction projects is to adopt Off-site construction (OSC) methodology, which enhances efficiency. The construction method selection is an important exercise toward the productivity and success of a building project. This exercise is particularly critical during the early stages of a building project, as it is important for decision makers to consider all criteria and make a prompt decision.

The use of off-site construction (OSC) is gaining popularity in building projects. Therefore, assessing the most relevant and key success factors in this context is necessary. Multiple Criteria Decision Making (MCDM) techniques have been widely used in the construction management domain. These are being applied as a medium for decision-making purposes in the construction sector. One of the most frequent methods is Fuzzy Logic to select an option among different alternatives based on a ranking system. In this paper, Fuzzy logic was applied to evaluate and rank the performance of two alternatives i.e. conventional method of on-site construction cast in situ works and Off-site construction steel structure fully modular approach. This project forms part of a Ph.D. research program which aims to develop a Two-Stage BIM-Lean Decision Support System (DSS) for the selection of a suitable Industrial Building System (IBS).

The proposed DSS development consists of two main steps: 1) Identification and evaluation of Key Decision Support Factors (KDSF) for the selection of the OSC approach and 2) Choosing an appropriate IBS for a building project. This paper focuses on the second step where fuzzy logic is applied to rank and select the appropriate alternative. A decision maker was provided with a list of Key Decision Support Factors (KDSF), which had been validated by industry experts, to input data and measure the importance and performance of each alternative. Crisp scores calculated using a fuzzy model indicated the rank of each alternative**.** The highest score of alternatives indicates the best approach. The result shows that alternative B – Off-site construction Steel Structure Modular approach, is the better option.

KEYWORDS

Off-site construction, Fuzzy Logic, Decision Making.

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INTRODUCTION

The construction industry is known for its subpar productivity when compared to other industries. It is common for large-scale construction projects to go over budget. The primary cause of these inefficiencies is a lack of productivity. While there are various reasons for this, adopting Off-site construction (OSC) methodology has proven to be an effective solution to improve efficiency in construction projects (Abdul Nabi & El-adaway, 2020). Using decision-making models in the Off-site construction (OSC) domain has improved project productivity and sustainability in building projects. Therefore, it is necessary to promote the OSC approach by proposing a comprehensive decision-making model from the perspective of the Canadian construction industry. While various forms of OSC systems are available in the market, there is a need for a comprehensive decision-making tool that can effectively aid decision-makers in swiftly and confidently selecting the appropriate method during the preliminary design phase (Daget & Zhang, 2019).

The process of selecting an appropriate construction method can be complex due to the many options available. Those responsible for making these decisions must take into account various factors and considerations to determine the most appropriate construction method. As a result, the process of selecting a suitable construction methodology is complex and involves multiple attributes and objectives (Attouri et al., 2022). Moreover, the selection of the construction approach method includes multiple factors and criteria which can turn it into a complex process. This paper is part of a more comprehensive project to develop a decision support system (DSS). The main focus of this project is to demonstrate and present the proposed methodology to assist a decision maker in the construction management domain. The authors employed a mixed method of qualitative and quantitative expert review in addition to a systematic literature review (SLR) to identify and validate the Key Decision Support Factors (KDSF) utilized for data collection and implementation.

RESEARCH BACKGROUND

Considering Off-site construction approach at the early design stage of the project would assist all the team members to “think offsite” which is very important for the success of the project (Attouri et al., 2022). In the construction industry, decision-making is an important and relevant task which can be supported by the use of computer technology to improve quality and efficiency in building projects (Marcher et al., 2020). Due to the complexity of the construction process and the variety of different techniques and methods in planning, manufacturing and constructing a building project, the significance of decision-making becomes prominent.

Earlier scholars have examined decision-making elements associated with Off-site construction. Wuni (2019) discerned the primary five factors involved in the selection of modular integrated construction (MiC) including the availability of skilled labour and management, project timelines, transportation, limitations in size, and equipment availability. The process of decision-making in the construction management domain based on Multi-criteria decision-making (MCDM) techniques has been reviewed by pioneer researchers such as Aboelmagd (2018), Alhumaidi (2015), An et al. (2020), Daget & Zhang (2019), and Ordoobadi (2009). Aboelmadg (2018) used Analytical Hierarchy Process (AHP) as a tool in MCDM to select the best constriction bid price. In that research, the benefits of MCDM techniques were demonstrated. Specifically, in the OSC domain, Daget & Zhang (2019) developed a decision-making model for the assessment of Industrialised Building System (IBS) using MCDM techniques. However, that research is limited to housing projects in Ethiopia.

There are different techniques in the MCDM approach. Ordoobadi (2009) applied fuzzy logic for the selection of a proper supplier capable of meeting the client’s requirements and demands. Daget et al. (2019) preferred to use the analytical hierarchy process (AHP) to develop a decision-making model in the OSC domain. Wuni (2020) developed a decision-making framework by determining fuzzy modelling to evaluate the critical failure factors for OSC projects. Poor design and lack of proper supervision and management were considered the main key failure factors for modular projects (Wuni & Shen, 2020). Ishuzaka (2014), compared the most widely used techniques in MCDM i.e. fuzzy logic, AHP, Fuzzy AHP (FAHP) and hybrid fuzzy AHP. Integration of Fuzzy logic with AHP is a new trend to overcome the challenges of uncertainties in the MCDM approach (Ishizaka, 2014).

This research is focused on applying fuzzy logic in the MCDM approach to evaluate and rank alternatives in a case study based on relevant factors that influence the decision making process in OSC building projects. The alternatives taken into consideration are Alternative A- Conventional method of onsite construction using cast in situ concrete works and Alternative B- Off-site construction steel structure fully modular approach.

RESEARCH METHODOLOGY

This section explains the methodology that will be applied in the case study, followed by an elaboration of the procedure for using Fuzzy Logic to rank each alternative. The data analysis calculation and results will be discussed in the next section. The selection of the proper construction method in this paper is part of a larger project that aims to develop a two-stage computerized decision support system (DSS) for selecting an appropriate Industrial Building System (IBS) in OSC projects.

The process of developing the proposed Decision Support System (DSS) consists of two main aspects: 1) identification and evaluation of Key Decision Support Factors (KDSF) for the selection of the OSC approach, and 2) choosing an appropriate approach based on a ranking system for a building project. This study mainly focuses on the second part, where fuzzy modeling is chosen to analyze and rank the alternatives. The list of KDSF validated in the first stage of the research project was used to collect data from a decision-maker to rank alternatives. The expert was asked to give a value to the importance and performance of each factor. A mixed method of quantitative and qualitative techniques was implemented to identify, validate, and assess Key Decision Support Factors (KDSF) for the selection of the OSC concept. The assessment of KDSF importance and relevancy resulted in generating a list of the system's suggestions of weighting based on the mean score ranking.

The list of the system's suggestions assists the decision-maker in proceeding with the application of the Multi-criteria decision-making (MCDM) model using Fuzzy logic. The expert can refer to the values suggested by the system and adjust them according to the nature of a specific project to determine the best judgment in this process. Fuzzy logic evaluation and modeling determine the ranking of the alternatives. Figure 1 shows the overall fuzzy modeling methodological framework applied in this project. However, this project is only focusing on Fuzzy logic analysis and system recommendations on the selection of the proper alternative.

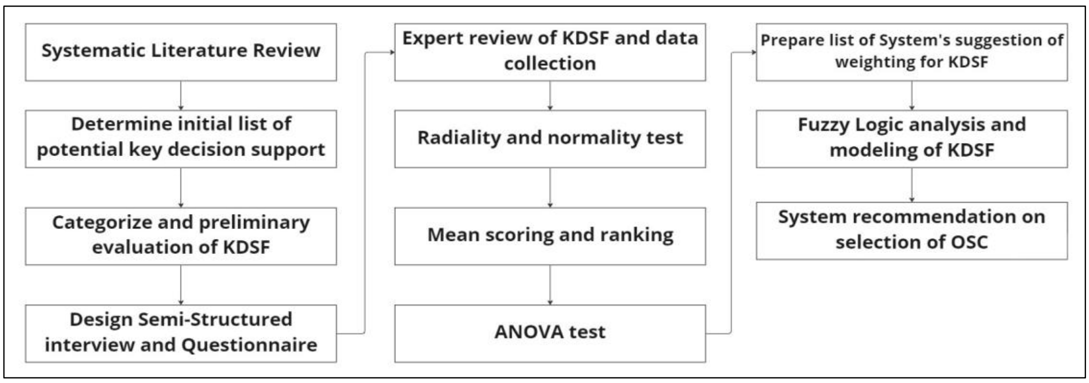

Figure 1: Fuzzy modelling methodological framework

The initial list of potential key decision support factors consisted of 32 factors that were categorized into seven dimensions. These were validated by 12 experts through semi-instructed interviews. A total number of 21 KDSFs were used to implement Fuzzy logic as per Table 1. A real case study was selected to assess the functionality of the proposed method. The selection process was based on the list of KDSF validated during the first stage and the expert's (decision maker's) weighting for each factor's importance and performance in stage two.

Table 1: Key Decision Support Factor (Main and sub-criteria)

Main Criteria	Key Decision Support Factor (KDSF)	Weights
Project characteristics (D1)	Project Location (F1)	w_1
	Project Design (Size, complexity and flexibility) (F2)	w_2
Supply chain (D2)	Financing (F3)	w_3
	Available Manufacturer (F4)	w_4
	Available Infrastructure (Hardware & Software) (F5)	w_5
	Available experts and skilled workers (F6)	w_6
Time (D3)	Design period (F7)	w_7
	Production time (F8)	w_8
	Mobilization & transfer time (F9)	w_9
	Assembly & construction period (F10)	w_{10}
Cost (D4)	Design (F11)	w_{11}
	Production & Manufacturing (F12)	w_{12}
	Logistics (F13)	w_{13}
	Assembly & Construction (F14)	w_{14}
	Maintenance (F15)	w_{15}
Quality (D5)	DfMA + Disassembly (F16)	w_{16}
	Standards and protocols (F17)	w_{17}
	Sustainability (Carbon emission, Energy consumption, waste) (F18)	w_{18}
Procurement (D6)	Type of procurement & delivery method (F19)	w_{19}
Socio-Cultural (D7)	Cultural resistance (F20)	w_{20}
	Local authority regulation (Workers Union-Syndicate) (F21)	w_{21}

The alternative weight given to each factor is based on the importance and performance scale given verbally by the decision-maker. For this case study, the value is assigned by an expert user with more than 10 years in OSC. Fuzzy logic is used to convert the 'linguistic' assessment into a numeric scale (Zadeh, 1965). The perception of the expert (decision maker) is based on 2 aspects, i.e. 1) the importance of each dimension (D_i) and 2) performance rating of DKSF (F_i). Ordoobadi (2009) applied membership functions consisting of two axes. The vertical axis represents the degree of membership and the horizontal axis represents the importance and performance scale (Ordoobadi, 2009). Table 2 and Table 3 respectively show the importance and performance of linguistic scale to fuzzy importance/performance. The importance of each dimension for each alternative is assessed by assigning a linguistic importance set of "Low", "Medium", "High" and "Very High" which correspond to their relevant fuzzy value on a scale of 0-1 as per Table 2. The membership functions of the linguistic importance weight and performance rate are based on the linguistic importance and performance scale presented by Ordoobadi (2009). The performance of an alternative with respect to each factor is evaluated on the linguistic scale of "Poor", "Good", "Very Good" and "Excellent" which correspond to a fuzzy value of 0-10 as per Table 3.

Table 2

Linguistic Importance	Fuzzy importance value
Low (L)	(0.0, 0.0, 0.2, 0.4)
Medium (M)	(0.2, 0.4, 0.4, 0.6)
High (H)	(0.4, 0.6, 0.6, 0.8)
Very High (VH)	(0.6, 0.8, 1.0, 1.0)

Table 3

Linguistic Performance	Fuzzy Performance value
Poor (P)	(0, 0, 2, 4)
Good (G)	(2, 4, 4, 6)
Very Good (VG)	(4, 6, 6, 8)
Excellent (EX)	(6, 8, 10, 10)

Equation 1 shows the calculation of the Fuzzy weight of a KDSF, where I_{Di} is an importance fuzzy value of a dimension and I_{Fi} is an importance fuzzy value of a factor. For example, the Fuzzy weight w_1 is calculated by multiplying the importance of project characteristics D_1 by the importance of size F_1 as per Equation 1.

Equation 1: $w_i = I_{Di} \times I_{Fi}$

The next step is to construct the fuzzy performance rate for each KDSF and to calculate the fuzzy score for each alternative. The fuzzy score of an alternative is calculated by multiplying the fuzzy performances by the fuzzy importance weights in a weighted sum according to equation 2, where fs_i is a fuzzy score, fp_i is a fuzzy performance and w_i is a fuzzy importance weight:

Equation 2: $fs_i = \sum_{i=1}^{n} fp_i \times \ w_i$; where *n = number of KSDF*

The final step is to rank the alternatives based on crisp scores. Fuzzy scores are defuzzified using the centroid method according to equation 3 where *(l,* m_l*,* m_u*, u)* construct fuzzy score. The alternative with the higher crisp score ranks first:

Equation 3: Crisp score $x = \frac{l+m_l+m_u+u}{4}$; where *l= first member,* m_l*= second member,* m_u*= third member, u= fourth member*

The following shows an example calculation of fuzzy weight w_i, fuzzy score fs_i and fuzzy performance fp_i:

Importance input by the expert for D1 (Project characteristics): High (H)

Importance fuzzy value for D1: (0.4, 0.6, 0.6, 0.8) = I_{D1}

Importance input by the expert for F1 (Project Location): High (H)

Importance fuzzy value for F1: (0.4, 0.6, 0.6, 0.8) = I_{F1}

$w_1 = I_{D1} \times I_{F1}$= (0.16, 0.36, 0.36, 0.64)

Performance input by the expert for F1 in Alternative A: Poor (P)

Performance fuzzy value for F1 in Alternative A: (0, 0, 2, 4) = fp_1

Fuzzy score for F1 in Alternative A: $fs_1 = fp_1 \times w_1$ = (0, 0, 2, 4) × (0.16, 0.36, 0.36, 0.64) = (0, 0, 0.72, 2.56)

As discussed earlier, among various techniques in MCDM, Fuzzy logic was selected for this project since it was necessary to show the importance of decision making in the early design stage of a building project while the amount of information and data might be very limited. By using Fuzzy logic compare to other methods such as AHP or FAHP, the decision making process is faster (Ishizaka, 2014).

RESULTS AND DISCUSSION

CASE STUDY

A real case study is presented to evaluate the application of the proposed method. The case study is a building project located in Canada that had a unique characteristic in terms of location, accessibility, and delivery time. The weather condition of the case study is characterized by extremely cold winter and short summer duration. Accessibility is very difficult, and the client's priority is to have an efficient building that can overcome challenges in that area such as proper thermal insulation, fast delivery and minimum building energy consumption. The decision maker was asked to provide input based on the list of KDSF to be considered for the selection of an appropriate construction method. The decision maker in this case was an expert with more than 40 years of professional experience in the construction industry. The list of KDSF criteria as per Table 1, consisting of 7 Main criteria and 21 sub-criteria, was used to develop the fuzzy model. The first input set was the importance values for the main and sub-criteria. Table 4 shows the importance rating for Project characteristics (D1), Project Location (F1) and Project Design - size, complexity and flexibility (F2) as an example.

Table 4: Importance rating for Project Characteristics (D1)

Main Criteria rate	Sub-Criteria rate	Weight
Project Characteristics (H)	Project Location (H)	w_1 = (0.16, 0.36, 0.36, 0.64)
	Project Design (VH)	w_2 = (0.24, 0.48, 0.60, 0.80)

The other weights are calculated in the same manner:

w_1 = (0.16, 0.36, 0.36, 0.64), w_2 = (0.24, 0.48, 0.60, 0.80), w_3 = (0.24, 0.48, 0.60, 0.80), w_4 = (0.16, 0.36, 0.36, 0.64), w_5 = (0.08, 0.24, 0.24, 0.48), w_6 = (0.24, 0.48, 0.60, 0.80), w_7 = (0.36, 0.64, 1.00, 1.00), w_8 = (0.24, 0.48, 0.60, 0.80), w_9 = (0.36, 0.64, 1.00, 1.00), w_{10} = (0.36, 0.64, 1.00, 1.00), w_{11} = (0.04, 0.16, 0.16, 0.36), w_{12} = (0.04, 0.16, 0.16, 0.36), w_{13} = (0.08, 0.24, 0.24, 0.48), w_{14} = (0.08, 0.24, 0.24, 0.48), w_{15} = (0.04, 0.16, 0.16, 0.36), w_{16} = (0.36, 0.64, 1.00, 1.00), w_{17} = (0.24, 0.48, 0.60, 0.80), w_{18} = (0.36, 0.64, 1.00, 1.00), w_{19} = (0.16, 0.36, 0.36, 0.64), w_{20} = (0.24, 0.48, 0.60, 0.80), w_{21} = (0.16, 0.36, 0.36, 0.64).

Table 5 shows alternative A - Traditional method and alternative B – Off-site construction (Modular) performance rating in the case study.

Table 5: Performance rating with respect to KDSF

Criteria	Rating of Alternative A	Rating of Alternative B
Project characteristics(D1)		
Project Location (F1)	P	EX
Project Design (Size, Complexity and Flexibility) (F2)	VG	G
Supply chain (D2)		
Financing (F3)	VG	VG
Available Manufacturer (F4)	P	VG
Available Infrastructure (Hardware & Software) (F5)	G	EX
Available experts and skilled workers (F6)	P	VG
Time (D3)		
Design period (F7)	VG	VG
Production time (F8)	P	EX
Mobilization & transfer time (F9)	VG	G
Assembly & construction period (F10)	P	EX
Cost (D4)		
Design (F11)	VG	VG
Production & Manufacturing (F12)	VG	VG
Logistic (F13)	VG	G
Assembly & construction (F14)	VG	EX
Maintenance (F15)	G	VG
Quality (D5)		
DfMA + Disassembly (F16)	P	EX
Standards and protocols (F17)	VG	VG
Sustainability (Carbon emission, Energy, waste) (F18)	G	EX
Procurement (D6)		
Type of procurement & delivery method (F19)	VG	VG
Socio-Cultural (D7)		
Cultural resistance (F20)	VG	G
Local authority regulation (Workers Union-Syndicat) (F21)	G	EX

Fuzzy score was constructed by using performance rating for each alternative with respect to the sub-criteria. Fuzzy scores of the alternatives were calculated by applying Equation 2 with respect to the expert's rating. The fuzzy scores were defuzzified by the centroid method determined in Equation 3. Finally, Alternatives were ranked according to their crisp score. The highest ranking was considered the most appropriate construction method for this project's specific case study. Table 6 summarizes the result. Alternative B- Off-site steel structure fully modular building, has a higher crisp score compared to alternative A- conventional method cast in situ concrete building. Therefore, the proposed fuzzy model ranked alternative A first. It is also supporting the critical success factors for this particular case study.

As mentioned earlier, due to the case study's location, weather conditions, accessibility, and specific client's quality requirement the factors of project location (F1), available infrastructure (F5), Production time (F8), assembly and production period (F10), assembly and construction cost (F14), DfMA + Disassembly (F16) and local authority regulation (F21) are major factors with higher performance value.

Table 6: Fuzzy score, crisp scores and ranking

Alternatives	Fuzzy Score	Crisp scores	Rank
Alternative A	(9.60, 31.76, 48.24, 94.56)	46.04	2
Alternative B	(18.72, 55.84, 81.76,124.96)	70.32	1

The finding of this research is also in line with discussions by previous scholars in this domain such as the study by Wuni (2019) on the five primary factors involved in the selection of modular methodology since skilled labour, project timeline, transportation, limitation in size and equipment availability have a similar perception to this study's factors with higher performance value. The significance of this study is the validation of the suggested alternative for the specific case study which is an ongoing project. The real scenario shows the reliability of the proposed system as well as its adaptability to other cases with different characteristics.

CONCLUSION

The decision-making process for selecting a suitable construction method is complex and influenced by many factors. It is an important process since a rapid and proper decision needs to be made at the early stages of a project. The initial selection of the most suitable approach will assist all stakeholders, such as engineers and architects, to develop their detailed designs in compliance with the specificities of the selected method (in the case study, the Off-site concept).

This project studied the application of fuzzy logic in the MCDM concept to select an appropriate offsite construction approach. The decision maker was asked to rank their preferences in a linguistic manner using a given scale to address subjectivity during data collection. These data were used to measure the importance and performance of Key Decision Support Factors. For the specific case study used in this project, Alternative A is the conventional method of cast-in-situ concrete works on site, while Alternative B is the Off-site steel structure fully modular building. The results show that Alternative B, with a crisp score of 70.32, ranks first, while Alternative A scored 46.04 and ranked second. Since the case study of this project was an ongoing modular project, the decision maker could validate the suggestion of the proposed Decision Support System (DSS) and its functionality.

The outcome of this research provides a useful and applicable framework to support the management process to reduce failure risk and improve the decision-making process. The proposed framework can be relevant and applied to any similar context, such as the comparison between various types of Industrial Building Systems (IBS). The importance and performance of relevant KDSF may differ in other countries and different types of construction projects, such as infrastructure, which are excluded from this study. Therefore, a future comparative study is suggested to investigate these differences. This project is limited to the use of data input by one expert. Furthermore, future research aims to collect more data to cover a larger context.

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IMPROVING PREMANUFACTURING PHASES IN OFF-SITE CONSTRUCTION THROUGH A DIGITALIZATION APPROACH

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ABSTRACT

The integration of digitalization and building information modelling (BIM) has been lauded as a cornerstone to improve processes and enhance communication across the construction industry. Nevertheless, the implementation of digitalization approaches has suffered due to the lack of methods and processes uncertainties, particularly in the case of off-site construction (OSC) companies where its premanufacturing phases (design, planning, and procurement) differ significantly from traditional construction. This research presents a case study of a digitalization-based workflow to reduce the duration and increase accuracy of premanufacturing phases. To that end, a digitalization plan is developed using value stream maps, supported by Monte Carlo simulation, to identify the waste of current practices and propose suitable improvement measures. Afterwards, a digitalization-based workflow is developed and implemented to exchange data between BIM models and other systems. After one year and a half of implementation, the proposed workflow reduced the duration of tasks in 92.31% while providing an average of 12.24% more accurate bill of materials compared to the previous approach. As such, the contribution of this study is twofold: first, a lean-based method to implement digitalization in OSC companies considering its particularities and inherited process uncertainties; and second, an improved process for OSC premanufacturing phases.

KEYWORDS

Off-site construction, digitization, BIM, simulation, value stream.

INTRODUCTION

Off-site construction (OSC) is characterized by its fast approach in construction where building components are manufactured in a shop floor meanwhile civil and foundation works are performed onsite. Although known for its performance onsite, Barkokebas et al. (2019) attributes the success of OSC to its integrated project delivery approach where premanufacturing (e.g., design, planning and procurement) phases are performed by the OSC contractor to design, procure materials, and develop shop drawings for production and final installation onsite. By adopting this approach, the OSC contractor transfers a significant risk

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from the client to themselves as they become responsible for all activities from the provision of engineering services up to the partial or full execution of the project.

To that end, OSC requires expedited procurement processes to account for variances in product and short lead times thus demanding digitized processes to aid in transparent coordination and accurate pricing (Oti-Sarpong, 2019). Additionally, Zheng et al. (2021) suggest the use of digitalization strategies to exchange data between stakeholders and automate processes to streamline premanufacturing phases given the complexity and risks involved in this approach. In this context, building information modelling (BIM) appears as an emerging trend of digitalization as it provides a representation of the intended project while exchanging accurate data (Wen et al., 2021). Indeed, Singh (2019) argues that, despite lagging behind other sectors, digitalization efforts are revamped in the construction industry due to the increased level of maturity in areas such as BIM, analytics and industrialization. Therefore, the development of BIM-based methods is a cornerstone for the advancement of digitalization strategies in OSC given its complexity and intrinsic integration in design and procurement phases.

The objective of this paper is to propose a case study involving the digitization of premanufacturing phases in the largest OSC wood-frame contractor in Brazil. By identifying wastes in current practices, this paper proposes a digitized workflow assisted by a BIM-centric add-on to automate customized quantity takeoffs as means to exchange data to streamline premanufacturing phases and assist in the accurate pricing considering different types of projects. To that end, the following hypothesis is tested: *a BIM-lean digitalization of premanufacturing phases will lead to lower development times and more accurate estimates of OSC projects*. To test this hypothesis, this paper provides methods for the digitalization of premanufacturing phases in OSC companies through a case study that can be later adapted and applied by other researchers and practitioners.

LITERATURE REVIEW

BIM has been heavily studied in the context of OSC in different areas such as constructability, exchange of data, and automation of design and procurement processes. Gbadamosi et al. (2019) propose a BIM-based system to evaluate optimal solutions for the design of elements and materials considering different factors such as the ease of assembly of handling parts, production rate, and waste in OSC projects. Additionally, Rausch et al. (2019) apply Monte Carlo simulation for tolerance analysis in the manufacturing of steel frame module while indicating if rework is required or not. To bridge the gap between design and manufacturing teams, An et al. (2020) propose the use of an ontology to establish a formal link between BIM models and knowledge from manufacturing experts to detect what operations can or need to be performed to manufacture wall panels.

Despite relevant BIM efforts and digitalization, Mukkavaara et al. (2018) argue information is segregated between different stakeholders in OSC projects and requires manual operations to ensure an information flow between systems. Additionally, they point out the importance of automation of contributory activities such as the development of bill of materials (BOM) from BIM models as a key feature for more interactive and digitized processes in OSC. With that in mind, Hussamadin et al. (2020) propose a conceptual model for the conversion of BOM extracted from BIM models to assist different stakeholders from off-site and onsite operations.

To address the issue of manual interpretations from estimators to perform takeoffs, Tang et al. (2022) propose rule-based algorithms to automatically detect takeoffs specific to OSC manufacturing operations. Besides comprehensive applications involving the automation of takeoffs in OSC, there is a lack of studies considering different types of project whereas the addressed papers refer to single case studies only. Despite significant studies to digitize OSC premanufacturing phases applying BIM, Oti-Sarpong (2019) points out the scepticism of practitioners to adopt these approaches due to a natural resistance to innovation from the industry and its inherited uncertainties. Schimanski et al. (2019) voice similar concerns pointing out the need for structured approaches to implement and maintain digitalization approaches in OSC. They also suggest lean thinking as a guiding principle for the implementation of digitalization approaches through the combination of construction-related data generated through premanufacturing phases of OSC projects and BIM models. Moreover, more implementations are needed to assist practitioners and propose methods to digitize OSC premanufacturing phases considering a holistic approach between different stakeholders and the exchange of data between them. To that end, Barkokebas et al. (2021) developed a framework for addressing the impact of digitalization in OSC by adopting a BIM-lean approach. Within the proposed framework, BIM models are used to improve processes and exchange data between teams (e.g., architectural, structural, etc.) while lean-based metrics are applied to evaluate the impact of digitalization in OSC premanufacturing phases.

RESEARCH METHODS

This study applies a case study approach to demonstrate the implementation of a digitalization-based workflow and test the proposed hypothesis. For this purpose, the unit of analysis to test the proposed hypothesis is a comparison between the development times and accuracy of the affected tasks before and after the implementation of the proposed workflow. A case study approach is applied due to its capacity to describe and offer insights on the object of interest (i.e., the effect of digitalization in OSC) (Yin, 2013). Figure 1 shows the research steps followed in this study where the first three steps are achieved by applying a framework developed by Barkokebas et al. (2021) to acquire a digitalization plan containing improvement measures in the case company based on the inherited uncertainties of its premanufacturing tasks. This framework applies value stream mapping (VSM), leveraged by Monte Carlo simulation, to identify waste in the current workflow while suggesting digitalization-based improvement measures that are applicable to the case company. Monte Carlo simulation is applied in this framework to quantify the inherited uncertainties of tasks identified during the development of VSM maps. During the development of VSM maps, durations are often provided by company experts in ranges (e.g., worst-case scenario, best-case scenario, and normal duration) instead of fixed durations to better understand the variability of their tasks.

Indeed, the applied framework asserts the duration of tasks as triangular distributions based on scenarios (pessimistic, realistic, and optimistic durations) provided by experts at the case company. Moreover, tasks are categorized in the VSM as value-added (i.e., productive), contributory (i.e., task necessary to perform the work that do not add value), and waste (i.e., non-contributory work) according to Pérez and Costa (2018). At the end of the framework's implementation, a digitalization plan is provided containing different improvement measures tailored to the context of the case company. Based on the digitalization plan, the case company decides which measure to implement whereas a digitalization-based workflow is designed and implemented. Different interactions between authors and company experts are performed during the implementation of the improvement measure so feedback is incorporated, and better results are achieved during evaluation. After implementation, the proposed workflow is evaluated by comparing the waste and other metrics identified during the development of VSM maps. After the comparison step, the hypothesis is addressed and the results of the proposed workflow are published. In total, the mapping process (i.e., first step of the digitalization plan) was developed in one month followed by another two months of implementation of the approved improvement measure. Finally, a comparison of results between the previously mapped and modified processes is presented after one a half year of its implementation.

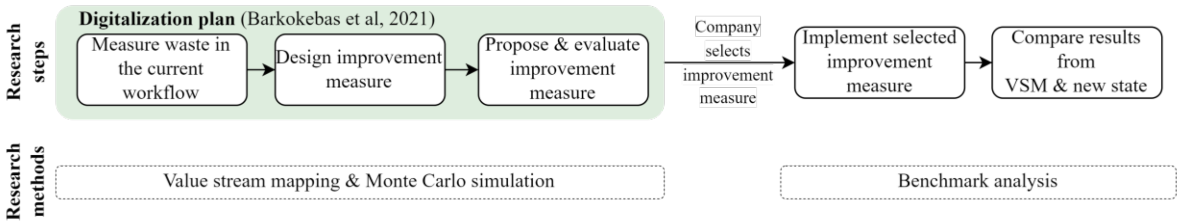

Figure 1: Research steps and methods according to DSR

CASE STUDY

As previously mentioned, the case study involves the work developed with the largest wood frame OSC company in Brazil specialized in the residential sector. The case company must adapt drawings provided by the client often designed to be built in masonry onsite (Brazil's most common construction method) to wood frame panels (walls, floors and roofs). Wall and floor panels will be manufactured on a semi-automated shop floor and later installed onsite while the roof is built onsite. Five premanufacturing teams are identified in the company: (1) project management office (PMO), responsible for estimating, preparing commercial proposals, and bidding for new projects; (2) architecture, responsible for preparing all architectural drawings and documentation for manufacturing and construction; (3) the design for manufacturing and assembly (DFMA) team, responsible for elaborating drawings and plans for the manufacturing and assembly of the manufactured panels; (4) plumbing, responsible for all plumbing drawings and documentation; and (5) electrical, who is responsible for all electrical drawings and documentation. All teams must upload its drawings, models and other documentation (BOM, estimates, schedules, etc.) in an enterprise resource planning (ERP) system. The following section will show the results of the digitalization plan according to the framework developed by Barkokebas et. al. (2021). Afterward, the results of the implementation of the proposed digitalization plan, the digitalization-based workflow, is presented followed by a discussion of similar studies.

RESULTS & DISCUSSION

DIGITALIZATION PLAN

Measure waste in the current workflow

Initially, the overall workflow is mapped to identify the exchange of information between teams on each project. This process is performed through semi-structured interviews performed online with each team's manager followed by other meetings to validate the information provided previously. Figure 2 shows the overall workflow and exchange of information between different teams followed by the main software used at the time. PMO receives the drawings in computer aided design (CAD) format from clients where manual takeoffs are performed to estimate the project's cost and the commercial proposal is delivered for bidding. Changes in the initial design by the client are common, thus the takeoffs must be updated so the commercial proposal reflects the latest project version, and the case company is competitive during the bid. A BIM model is not developed at this point due to the significant effort to develop the model where takeoffs are the only information needed. Moreover, the PMO argues that the significant effort is not justified since the project is still in the bidding stage whereas the case company still does not know if it will win the bid or not. Hence, quantity takeoffs are performed on AutoCAD and manually transposed to MS Excel for cost estimation.

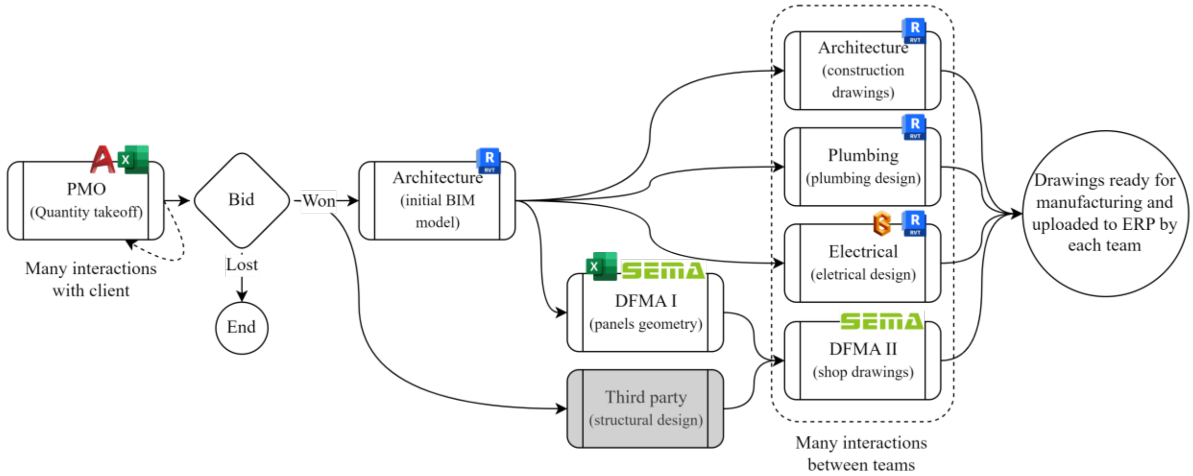

Figure 2: Overall workflow between teams

If the bid is won, the latest version of the project is sent to a third-party structural consultant and the architectural team starts developing the initial BIM model so the remaining teams (electrical, plumbing and DFMA) can start their work using BIM authoring software. At this point, Autodesk Revit is used as the main BIM authoring software by most teams. The initial BIM model includes all panels (floors, walls, and roofs) with its openings, thus delimitating the spaces and overall geometry of building elements in the project. Architectural and construction specifications are defined by the architectural team during the design process whereas decisions are made and coordinated with the remaining teams. The electrical and plumbing teams develop the drawings and specifications of their respective disciplines using Autodesk Revit whereas the electrical team also utilizes a specialized software (AltoQi Builder) to perform calculations. Meanwhile, the DFMA team is responsible for adjusting building elements according to the case company's manufacturing and construction methods. At the beginning of the project (i.e., DFMA I in Figure 2), the DFMA team defines the exact geometry of panels according to previous projects. After structural design is finished by a third-part consultant, the DFMA team revises the geometry of panels and generates shop drawings for manufacturing in the shop floor leveraged by semi-automated machines (i.e., DFMA II in Figure 2). Hence, the DFMA team utilizes SEMA, a specialized software in wood construction, to generate the shop drawings and computerized numerical control (CNC) codes to be use in the semi-automated machines. Due to different software used, data between the DFMA and electrical teams is exchanged using industry foundation class (IFC) format. Since the remaining teams use the same software (Autodesk Revit), data between them is exchanged through native files.

Some of the identified challenges are the loss of data and productivity when using heavy IFC models (DFMA and electrical teams) and the lack of documented design solutions and material consumptions used in previous projects (PMO and DFMA teams). All teams, except for PMO, also pointed out the extensive time required to develop the project documentation while maintaining all information updated during project revisions. Nevertheless, the most common challenges, identified by all teams, are associated with the exchange of data related to takeoffs where schedules created automatically in Revit and other software need to be transposed to spreadsheets or ERP following manual procedures. Indeed, every team needs to perform quantity takeoffs and provide schedules such as BOM to account for the cost of each discipline. Specialized software used by the DFMA and electrical teams provide automated BOM for each discipline. However, automated schedules developed by the remaining teams using Autodesk Revit needs to be transposed and modified manually in Excel to include all materials required without the need of extra modelling in the BIM model. Furthermore, teams indicate that takeoffs are often outdated after several project revisions due to the error-prone and extensive time spent on revising updated takeoffs due to changes in the models. After all teams are finished, this information is uploaded by each team to the case company's ERP system so material can be ordered and the project is scheduled for manufacturing by other departments.

The architectural team was selected for the application of the proposed framework and to evaluate whether it would benefit from a digitalization-based workflow. This team was selected because it provides the base BIM model to the remaining teams and is responsible to determine the actual quantities related to the architectural discipline. Hence, a VSM is developed to map current waste in the architectural team considering the inherited uncertainty of design processes applying a Monte Carlo simulation using Simphony.NET software.

Table 1 shows the tasks identified during interviews with the architectural team manager to develop the VSM supported by the Monte Carlo simulation. Tasks are performed in the order described in the table and are categorized as per value-added, contributory work or waste according to lean philosophy (Pérez & Costa, 2018). The initial three tasks in Table 1 correspond to the first process from the architectural team (i.e., initial BIM model) in Figure 2 whereas the remaining tasks in the table correspond to the second process (i.e., construction drawings) demonstrated in the same figure. As previously mentioned, task durations are given by experts in the form of scenarios (pessimistic, realistic, and optimistic) which, in turn, are modelled as triangular or uniform distributions depending on how the information is gathered by experts. Table 1 shows only one task categorized as waste which entails developing the initial BIM model from the latest CAD drawings while the most impactful contributory work is related to the takeoff and exchange of data process once this design phase is finished. Therefore, the observations made during the interview process with all premanufacturing teams confirms the significant effort in exchanging data as supported by the data displayed in Table 1 where the takeoff and exchange of data task amounts over 30% of the total average duration. The results of simulation are presented in the Propose & Evaluate section together with the proposed scenarios.

Table 1: Input for simulation model

Task description	Task type	Duration (days)		
		P	R	O
Develop initial BIM model	WT	2	1	0,5
Determine location of electric outlets	VA	1		0,5
Send initial BIM model to other disciplines	VA		0	
Review project scope	CW	0,3		0,2
Architectural detailing	VA	3–4	2	1
Roof detailing	VA		1,5	
Construction detailing	VA	5	4	3
Waterproofing detailing	VA	2	1	0,5
Develop views for federated model	CW		0,5	
Quantity takeoff and exchange of data	CW	4,5	4	3

Note(s): VA: Value-added, CW: Contributory work, WT: Waste, P: Pessimistic scenario, R: Realistic scenario, O: Optimistic scenario.

Design

In light of what was mapped and considering the current waste in the architectural team, two improvement measures are suggested by the authors: (1) the development of an add-on to generate BIM elements (walls, floors, and openings) from the latest CAD drawings approved during bid by the client , and (2) the development of a workflow to automate the exchange of data between BIM models and other systems (e.g., ERP) leveraged by an add-on and coupled with the adaptation of currently used MS Excel formulas to increase the speed and accuracy of takeoffs during the design process.

The first suggested measure (i.e., add-on in Autodesk Revit to generate BIM models from CAD files) aims to minimize the only task categorized as waste while ensuring the remaining teams start working as soon as possible. The nature of this task also involves time-consuming and repetitive work without requiring specialized expertise thus becoming an ideal candidate for automation. Moreover, the proposed add-on is also applicable to PMO during the cost estimation phase where a BIM model can provide accurate data without the expense of extensive development time. The second suggested measure aims to automate the takeoff process exchange of data between the BIM model and other systems in the case company. This data is used to provide information related to the quantity of materials, cost and production schedules required during the procurement and manufacturing phases which are uploaded to the ERP system. The development of an add-on for Autodesk Revit is suggested to generate CSV files containing the required data for the entire project that will be uploaded in the existing MS Excel spreadsheets used by the case company. The main difference between the current process and the proposed workflow involves the automated exchange of data from the entire project whereas manually updating information from BIM-based schedules results in mistakes and extensive time to make sure all information is updated and correct. Furthermore, this workflow is also applicable to other teams using Autodesk Revit (Plumbing and Electrical) in case the proposed workflow is accepted by the architectural team. It is important to note that both improvement measures are developed based on previous studies and the experience of authors in similar OSC companies. Therefore, other suggestions may be applicable depending on different experiences if other participants were involved.

Propose & Evaluate

This section provides an evaluation of the impact that the proposed suggestions will have in case they are implemented. To do so, the duration of affected tasks by the improvement measures are adjusted in the validated Monte Carlo simulation to predict changes in the average project duration. The modified tasks durations are estimated according to the author's

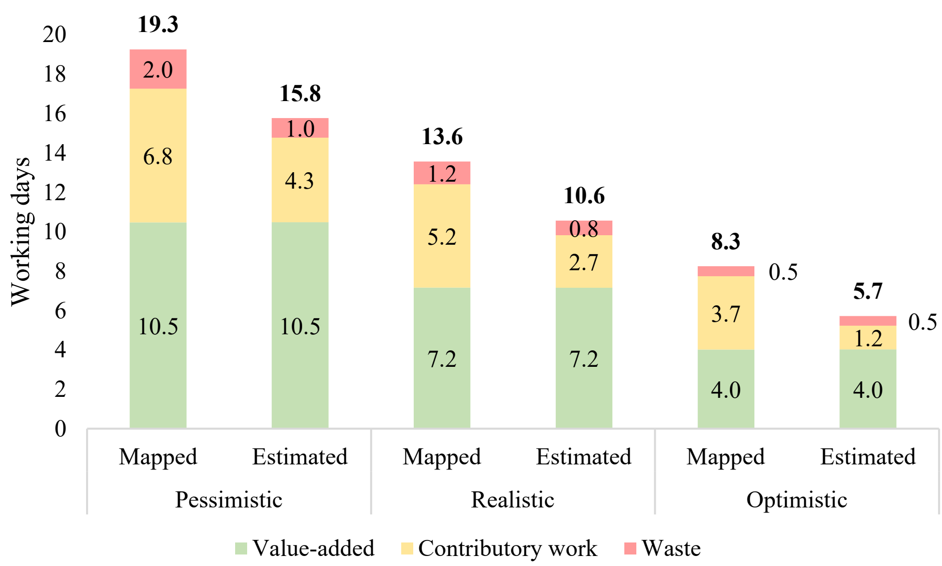

Figure 3: Comparison between the mapped and estimated durations according to different scenarios and task types

experience and in discussion with the case company's experts. The first and second suggested measures will reduce the duration of each task significantly. In the case of the proposed add-on to generate BIM models from the latest CAD drawings (i.e., first suggested measure), authors estimate the task "Develop initial BIM model" will take between half to one working day (e.g., pessimistic and optimistic scenarios, respectively) in case this measure is implemented. Moreover, on the second suggested measure, authors propose an add-on to automate the takeoff and exchange of data process between Autodesk Revit and Excel to reduce the task "Quantity takeoff and exchange of data" between half to two working days (e.g., pessimistic to optimistic scenarios, respectively) considering the size of projects and team's productivity. Hence, the validated Monte Carlo simulation is updated with uniform distributions (i.e., 0,5 to 1 working days in the case of the first modified task) according to what was estimated by authors and compared to the mapped state of durations. Figure 3 shows a comparison between the mapped durations and estimated durations according to what was gathered with the architectural team and author's experience, respectively. Also, the figure shows the total average project duration (in bold) while highlighting the contribution of each task type according to different scenarios. According to Figure 3, the total project's duration can be reduced 23,84% on average in case both measures are implemented. After this assessment, the digitalization plan was completed, and the case company experts could decide to implement the proposed measures or not.

PROPOSED DIGITALIZATION-BASED WORKFLOW

Implementation of selected improvement measures

Based on the digitalization plan developed in the previous subsection, the architectural team decided to not move forward with the first suggested improvement measure and prototype the workflow leveraged by an add-on to automate the exchange of data between BIM models and other systems (i.e., second improvement measure). Therefore, an add-on to automate exchange of data between Autodesk Revit and Excel was developed since these software are currently used by the architectural team. Moreover, the developed addon is applicable to other design teams using Autodesk Revit to design their models while using Excel to import data to the ERP system. Since the ERP system requires specific access to develop applications in it, importing data via Excel was suggested as this is a common default feature in most ERP systems. Hence, in case it is approved by the architectural team, the proposed workflow is applicable for all design teams with the exception of PMO and DFMA. Figure 4 shows changes suggested in the architectural team according to the proposed workflow and leveraged by the developed add-on. The add-on, named BTO provides an automated connection between data embedded in the BIM model and takeoffs required by the design team using Excel as an interface. Once the required takeoffs are entered in an Excel spreadsheet, the spreadsheet is uploaded to BTO which collects the data from Autodesk Revit and returns it in a structured format in Excel. The takeoffs are then processed through formulas in Excel to account for material waste, and labor or materials that are not modelled directly in the BIM model (e.g., ceramic tile placed up to a certain height in wet areas are calculated from the wall length at a specified height).

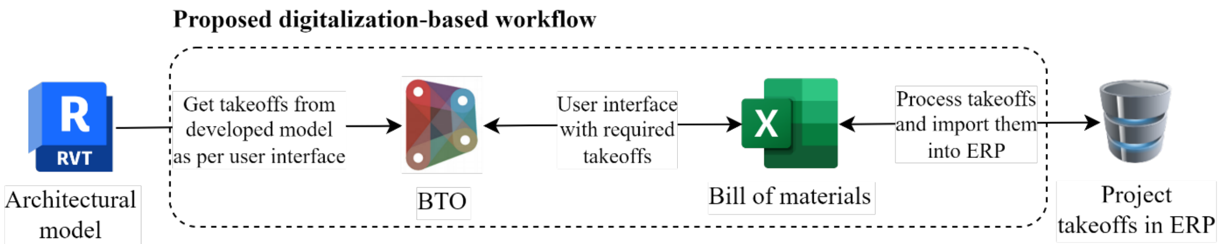

Figure 4: Changes in the current workflow

Comparison between mapped and proposed workflows

To address the hypothesis, this section shows a comparison of results between the previously mapped workflow and actual results gathered through interviews and data provided by the architectural team after implementation. Table 2 shows a comparison between the previously mapped and current durations and coefficients of variation, calculated using the program evaluation and review technique (PERT), in the affected task by the proposed workflow. The actual durations for quantity takeoff were gathered during interviews with the architectural team's manager after one year and a half of implementing the proposed workflow and add-on. Following the same procedure when developing the VSM maps, the actual durations of the affected task were gathered considering the inherited uncertainties (i.e., pessimistic (P), realistic (R), and optimistic (O) scenarios) of design processes as determined by Barkokebas et al., (2021). Table 2 shows that the proposed automated process, leveraged by the addon BTO, reduced the task in 92.31% % where the actual task duration varies between 0,2 to 0,5 working days. This result exceeded the expectation from authors where they forecasted 0,5 to 2 working days in the Propose & Evaluate section of this paper. This discrepancy is explainable with two reasons: (1) authors wanted to be conservative in their forecast while developing the digitalization plan, and (2) company experts modified formulas in their bill of materials so takeoffs could be performed more easily. Nevertheless, this result is aligned with previous studies comparing the application of BIM versus traditional approaches where takeoffs are consistently reduced by 70% of duration (Bečvarovská & Matějka, 2014; Wahab & Wang, 2022). The coefficient of variation increased significantly in the proposed workflow compared with the previously mapped workflow. Nevertheless, the manager of the architectural team indicated that, even when accounting for a more variable process, the duration in the takeoff process is greatly reduced by the proposed digitalization workflow.

Table 2: Task duration comparison between the mapped and proposed workflow

Task description	Scenarios			Expected duration (days)	Coefficient of variation
	P	R	O		
Takeoff and exchange of data (mapped)	4,50	3,80	3,00	3,90	6,38%
Takeoff and exchange of data (proposed)	0,50	0,30	0,20	0,34	14,43%
Difference between takeoff processes				**-92.31%**	**111,71%**

To assess the effect of the proposed workflow in the accuracy of estimates, the architectural team gathered data from three projects and compared their takeoffs performed by BTO with the BOM developed manually by the PMO team during the bidding phase. Table 3 shows the deviation between the manual and automated takeoffs on the main items surveyed by the architectural team. Deviations as significant as 80,3% confirm the high potential for error of manual takeoffs in the construction industry. Furthermore, an average 12,24% deviation between manual and automated takeoffs are observed between the three projects thus indicating that the automated takeoffs are significantly more accurate than the manual approach. Once again, this result is aligned with previous studies such as Pratoom & Tangwiboonpanich (2016) that indicate a deviation of 17,76% in the quantity of items considering manual and BIM-based takeoff practices. The results of improvements in both metrics established to test the proposed hypothesis (tasks durations and takeoff accuracy) are aligned with findings in previous literature as described in this section. Therefore, based on the results provided, the architectural team accepted the proposed workflow and decided to implement it in the entire team.

Table 3: Takeoff deviation between manual and digitalized processes

Material	Unit	Deviation from original takeoff (%)		
		Project 1	Project 2	Project 3
Ceramic tile	m^2	5,19%	12,44%	12,22%
Cementitious board	m^2	9,12%	16,78%	16,02%
Gypcrete	m^3	-15,15%	20,00%	7,03%
Ceiling	m^2	6,75%	7,21%	22,89%
Plaster board	m^2	8,71%	16,16%	4,04%
Water proofing	kg	-0,31%	61,82%	13,86%
Batt insulation	m^2	5,09%	45,39%	8,95%
Windows	un	0,00%	0,00%	0,00%
Painting	m^2	80,30%	6,76%	11,16%
Doors	un	0,00%	0,00%	0,00%
Roofing	m^2	9,10%	14,79%	7,75%
Exterior finishes	m^2	9,35%	7,45%	9,83%
	Average	**9,85%**	**17,40%**	**9,48%**

CONCLUSION

Despite relevant studies in the area, digitalization strategies and the use of BIM are still not fully implemented in OSC due to its inherited uncertainties and specific aspects compared to traditional construction. Aligned to that, the present study provides a practical implementation of a digitalization-based workflow in an OSC company aiming to reduce the current waste in its premanufacturing phases. Through the application of a framework developed by Barkokebas et al. (2021), the authors developed a digitalization plan supported by VSM maps and Monte Carlo simulations to identify current waste and propose improvement measures considering its potential impact to the case company. The digitalization plan identified two improvement measures to automate the generation of BIM models and the exchange of data between BIM models and other information systems, respectively. By selecting and implementing the second improvement measure, an add-on (i.e., BTO) was developed to automate the takeoff and exchange of data process and rendered a reduction of 92,31% in duration while providing more accurate BOM when compared to the previously mapped workflow. The achieved results performed better than expected in comparison to the estimated reduction presented in the digitalization plan. Yet, results were validated by the case company experts throughout interviews and based on the implemented digitalization-based workflow after one year and a half of its implementation. Given the positive results, the proposed workflow is incorporated in the case company. Despite its results, this study still presents limitations regarding the case study approach, as it becomes biased to the specific context of the case company and ultimately, cannot be generalized. Therefore, more case studies are needed to increase the number of methods to digitalize premanufacturing phases in OSC. Nevertheless, the hypothesis of this study is approved within this context since the case study demonstrates that the implementation of a BIM-lean digitalization approach results in lower development times and more accurate estimates when working with OSC companies. Finally, this study contributes with a lean-based method to implement digitalization practices in OSC companies considering its particular context and inherited process uncertainties to improve processes in OSC premanufacturing phases.

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INVESTIGATION OF THE SUPPLY CHAIN OF MASS TIMBER SYSTEMS

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ABSTRACT

How well production systems and their supply chains are designed, configured, and managed affects the delivery of construction projects. Industrialized Construction (IC) and mass timber present a shift from traditional project delivery: they are reshaping existing supply chains and creating new ones within the construction industry. The rapidly increasing number of mass timber projects in North America and the emergence of mass timber supply chains bring the need to study and seek ways to design and improve the production systems that deliver customer value by means of such projects. Accordingly, this paper presents an exploratory case study that describes the characteristics of the mass timber supply chain in North America and the major steps in the process of designing and delivering a mass timber structural system for a multi-story residential building. In addition, we present a list of recommendations for designing and delivering mass timber systems.

KEYWORDS

Mass timber, supply chain management, industrialized construction, off-site construction, production system design.

INTRODUCTION

The performance of construction projects—including mass timber projects—is tied to how well production systems and their supply chains are designed, configured, and managed. Being efficient on the jobsite is not enough. An integrated network of individuals and companies is key to ensuring that trade-offs are collaboratively evaluated, and optimal decisions are made during the design of products and processes. These in turn increase the likelihood of successfully delivering a project (i.e., providing the value that the customer expected). As O'Brien et al. (2008) point out, "it is difficult to address supply chain production improvements without also considering arrangements between organizations."

In the case of mass timber products and systems, due to the novelty of the material and the building codes that bring new design (not only product design but also process design) and use opportunities, the supply chains to deliver these products are still emerging and worthy of research. New businesses are emerging in many places, each one aiming to provide value for a part of the supply chain. Additionally, automated manufacturing equipment is becoming less expensive and increasingly versatile, which is encouraging companies to contemplate entering the Industrialized Construction (IC) and off-site fabrication world (ABB 2021) as they identify opportunities to deliver projects more economically, efficiently, and effectively.

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The opportunity for this study comes from three directions: (1) the rapidly increasing number of mass timber projects in North America (WoodWorks 2023), (2) the emergence of mass timber supply chains, and (3) the use of automated manufacturing equipment becoming more widespread in construction. Furthermore, given the lack of publications on how to design and manage the production systems to deliver projects (including mass timber projects) using IC, we see the need to study and seek ways to design and improve the production systems that will deliver customer value by means of such projects. These systems will be enabled by companies that use manufacturing principles, methods, and tools and strive to lower costs, shorten lead times, and increase quality.

Exploring the current state of the mass timber supply chain and the process of designing and delivering a mass timber structural system for a multi-story building is essential for formulating recommendations that will improve the efficiency and effectiveness of the mass timber industry. As part of ongoing research, this paper aims to answer the following questions: (1) What are the characteristics of the mass timber supply chain? and (2) What is the process of designing and delivering a mass timber structural system for a multi-story building? In response, we (1) introduce mass timber as a family of engineered wood products and as a structural building system, (2) present the reasons for its increase in use in the North American building industry, (3) describe some mass timber products used in building construction, (4) report on the emergence of the mass timber supply chain in North America, (5) explore the association of mass timber with IC, (6) describe the delivery process of a mass timber structural system for a multi-story building, and (7) provide a list of recommendations for designing and delivering mass timber structural systems.

SUPPLY CHAIN MANAGEMENT IN CONSTRUCTION

A supply chain is a network of entities involved in the design, production, and delivery of products to customers. Supply chain management (SCM) is "the practice of a group of companies working collaboratively in a linked chain of interrelated processes designed to best satisfy end-customer needs while rewarding all members of the chain" (Tommelein et al. 2003). Companies need to decide, for example, either individually or collectively, what products to make, where to make them, and how to make them, and what products to purchase, where to purchase them, and from whom to purchase them.

The importance of managing supply chains comes from the potential that developing relationships, integrating processes, increasing transparency and alignment, and focusing on customer needs can enable organizations to gain an economic advantage over their competitors. SCM—a term used more widely since the 1980s (Ashcroft 2021)—originated in the manufacturing industry (Vrijhoef and Koskela 2000) and evolved significantly in the 20th century. A substantial advancement in SCM came from Just-in-Time (JIT) production, one of the pillars of the Toyota Production System (TPS) (Liker and Meier 2006). JIT production is concerned with providing only the necessary quantity of items to each process in an assembly sequence, only when needed. The principles of the Lean production philosophy that constitute the TPS inspired the conceptualization of Lean Construction in the 1990s. The study of construction supply chains, which is a more recent phenomenon than the study of manufacturing supply chains, is closely related to the emergence of Lean Construction. Both adopt a systemic view of production systems.

Construction supply chains have been studied by several authors including Vrijhoef and Koskela (2000), who presented four roles for SCM, Arbulu and Tommelein (2002), who studied the supply of pipe supports used in power plants, Akel et al. (2001), who studied practices of parametric product design, vertical integration, and Lean construction in a pre-engineered metal building company, and Souza and Koskela (2013), who proposed a set of contextualized practices for improving construction SCM. Construction supply chains are arguably among the most complex supply chains to study and manage due to several factors, including (1) the temporary nature of projects, (2) the large number of stakeholders, (3) the wide variety of products and services, (4) the need for customization of products (e.g., Engineered-to-Order or ETO products) (5) long lead times, (6) disruptions caused by the existence of global supply chains, (7) regulations, codes, and standards, and (8) market volatility. Additionally, built assets—the finished products of these construction supply chains—are not only unique products (or prototypes) but they also require capital-intensive investment. These factors all have contributed to the existing fragmentation of construction supply chains. This fragmented nature has culminated in a business with low-profit margins, high risk, and a huge amount of waste—not only material (physical) waste but also waste from inefficient processes. Although a focus of construction management research has been on improving on-site processes, the uptake of off-site construction and IC means that a broader view of the design and aspects of supply chains is needed. Accordingly, and given the growing number of mass timber projects, this paper focuses on studying the supply chain of mass timber.

STRUCTURAL WOOD BUILDING SYSTEMS

In North America, wood structural materials have been used mainly in the construction of single-family homes and low-rise residential, commercial, and industrial buildings. Light-frame wood construction is the predominant structural wood building system in North America. It has dominated the North American housing market (both single- and multi-family) since the latter part of the 20th century and is also widely used in low-rise commercial and light industrial applications (Ross 2021). The vast number of builders with experience in light-frame wood construction and the relatively low cost and off-the-shelf availability of the materials (e.g., lumber, plywood, and fasteners) and tools used in this type of construction have contributed to its predominance in North America.

Other types of structural wood building systems such as post-frame, log, and heavy timber construction have also been used for decades in North America. In the early 1990s, cross-laminated timber (CLT) was invented in Europe and began to define a new family of engineered wood products known as mass timber. The use of CLT increased significantly in Europe in the early 2000s, driven by the green building movement and the increased efficiencies achieved with the fabrication and installation of CLT (Karacabeyli and Douglas 2013, p. 1). Other mass timber products include products that have existed for decades such as glued-laminated timber (glulam or GLT), nail-laminated timber (NLT), and others developed more recently, such as dowel-laminated timber (DLT), mass plywood panel (MPP), and mass plywood lam (MPL).

MASS TIMBER CONSTRUCTION

The term “mass timber” (with “mass” referring to “massive”) refers to a family of engineered wood products (or structural building systems) that are made of multiple compressed solid layers of wood joined together with glue, dowels, or nails, forming large solid wood elements such as CLT, glulam, NLT, DLT, MPP, or MPL. These products are manufactured (additive manufacturing) to various sizes and later processed or fabricated (subtractive manufacturing), usually off-site and according to a set of fabrication shop drawings. In the fabrication process, mass timber elements are cut to size, hollowed to make openings for penetrations to allow for the passage of Mechanical, Electrical, Plumbing, and Fire Protection (MEPF) elements, receive fire protection and connections, and are sealed. This turns mass timber elements into custom (ETO) building components. These components are then delivered to a jobsite as a kit of parts to be assembled. They are generally used for load-bearing purposes (e.g., columns, beams, floors, walls, stairs, and roofs) but can also function as an interior finish material (e.g., walls).

Although timber framing is not a new concept, it was the invention of CLT that now enables the construction of taller wood structures. Successful fire tests supported the inclusion of mass timber as a structural material into the 2015 IBC (ICC 2015), allowing mass timber buildings up to 6 stories (commercial projects) or 5 stories (residential projects) and about 26 m (85 ft.) in height. This spearheaded the development and construction of hundreds of mass timber projects in the United States (US). The most recent IBC (ICC 2021) went even further, introducing three new construction types that allow mass timber buildings of even taller heights, more stories above grade (up to 18 stories), and greater allowable areas.

Sustainability has been a major driver for the use of mass timber. Compared to alternative materials such as steel or concrete, the benefits of mass timber construction are significant, both in embodied carbon reduction because it requires much less energy to produce and in the long-term storing of carbon in the wood (carbon sequestration). That being said, mass timber products are only as sustainable as the process used to harvest, transport, and manufacture them, which explains why embodied carbon data can vary between different mass timber manufacturers. Nevertheless, mass timber construction also offers other benefits such as aesthetics and efficiency gained through off-site fabrication, which can accelerate construction (resulting in schedule savings) and reduce on-site labor.

The mass timber movement in North America has been fueled by more manufacturers entering the market, architects, engineers, and builders acquiring expertise in the design and construction of mass timber, and the advancement of digital processes, workflows, tools, and equipment. This has given rise to mass timber being now considered one of the most suitable building materials or systems for IC and off-site prefabrication. Mass timber systems are also included in the Modern Methods of Construction (MMC) framework (MHCLG 2019).

Because mass timber is a relatively new system, oftentimes owners and designers will compare it to alternative structural systems to decide on the most appropriate one. Therefore, we suggest using a sound decision-making system like Choosing by Advantages (CBA). CBA is a system that considers value expressed by means of advantages of alternatives relative to one another, and makes comparisons based on those advantages, without considering money (cost or price) until after attributes of alternatives have been evaluated based on factors and criteria (Suhr 1999). Examples of CBA applications in the AEC industry were presented by Parrish and Tommelein (2009) and Arroyo et al. (2012, 2013). Factors that can be used with the CBA system to compare mass timber construction to other types of construction include but are not limited to (1) building type, (2) building height, (3) building and floor areas, (4) fire resistance, (5) structural strength, (6) sustainability, (7) aesthetics, (8) material availability and lead time, (9) site logistics, (10) on-site work and schedule, (11) off-site work and schedule, (12) material sizes, (13) tolerance management, (14) industry knowledge, (15) insurance availability (e.g., builder's risk and property), (16) integration with other building systems, (17) transportation and logistics, (18) use of technology during design and fabrication, and (19) material durability.

Next, we provide a categorization of some of the most used mass timber products in North America with their usual applications and dimensions. Knowing what products are offered and what they can be used for is fundamental when studying SCM and designing production systems because different products may require different processes and resources.

GLUED-LAMINATED TIMBER (Glulam)

Glulam is a wood element composed of lumber boards that are joined end-to-end and bonded by means of structural adhesive. The grain of the laminations runs parallel with the length of a glulam. Glulam elements are commonly used as beams and columns. They can be straight or curved and are stress-rated. They are available in four appearance classifications: (1) framing, (2) industrial, (3) architectural or commercial, and (4) premium. Glulam elements fabricated in North America are typically between 7.5 cm (3 in.) to more than 50 cm (20 in.) wide, 10 cm (4 in.) to more than 150 cm (60 in.) deep, and up to 18 m (60 ft.) long.

CROSS-LAMINATED TIMBER (CLT)

CLT is a large-scale solid, straight, and rectangular wood panel that consists of an odd number (usually three, five, seven, or nine) of layered lumber boards stacked in alternating directions, bonded by means of structural adhesive, and pressed. CLT panels can be used as load-bearing elements and applications include floors, walls, and roofs. Panels fabricated in North America are typically up to 3.6 m (12 ft.) wide, up to 18 m (60 ft.) long, and up to 32 cm (12.5 in.) thick.

MASS PLYWOOD PANEL (MPP) AND MASS PLYWOOD LAM (MPL)

MPP and MPL consist of multiple layers of 2.5 cm (1 in.) thick lamellas joined together, with each lamella constructed of multiple layers of thin veneer that are glued and pressed together (Freres Engineered Wood 2023). Lamellas are stacked in alternating directions in an MPP (like CLT) while they are stacked end to end in an MPL (like glulam). MPP is certified as a CLT panel and can be used in identical applications. MPL elements can be used as beams and columns, like glulam elements. MPP fabricated in North America are typically up to 3.6 m (12 ft.) wide, up to 14.6 m (48 ft.) long, and up to 30.5 cm (12 in.) thick. MPL are typically up to 61 cm (24 in.) wide, up to 121 cm (47.5 in.) deep, and up to 14.6 m (48 ft.) long.

MASS TIMBER SUPPLY CHAIN IN NORTH AMERICA

CLT panels combined with glulam beams and columns were used in 2012 as a structural system for the first time in North America (Structurlam 2019). The high-volume manufacturing of mass timber products requires the use of specialized equipment to, for example, apply adhesive between lumber boards and press the lumber boards together. For this reason, even though the US and Canada have a long-established lumber industry, the mass timber supply chain is still young and relatively small but is rapidly growing.

The Pacific Northwest region of the US and the Canadian province of British Columbia are home to forests that provide softwood of good quality (e.g., spruce, pine, fir, and Douglas fir) to manufacture mass timber products. Not surprisingly, this region houses not only the largest number of mass timber suppliers but also the largest number of mass timber projects in North America. Some of these suppliers focus on the manufacturing of Fabricated-to-Order (FTO) mass timber products. FTO products are those "put together from parts that are already designed, but as-of-yet have to be made, so as to meet the specifics of a customer request" (P2SL 2023). In the case of FTO products, a customer provides a list of mass timber products with their exact quantities and sizes, and the supplier (manufacturer) manufactures them to size, without having to redesign or engineer these parts. Other suppliers focus on the fabrication of ETO mass timber products. ETO products are those for which design and engineering are done in response to a specific order from a customer, and the product is then made according to those design specifications (P2SL 2023). In the case of ETO products, a customer provides, e.g., structural- or architectural drawings and the supplier (fabricator) needs to create fabrication shop drawings so that all openings and connections can be included according to those drawings.

Some mass timber products have been manufactured and used for decades in North America. For example, the first glulam structures were erected in the US in the 1930s, although the first American manufacturing standard was published only in 1963 (APA 2023). Significant advances have been achieved during this time, particularly with respect to the adhesives used to join lumber boards during the manufacturing of glulam.

Other products, such as CLT, MPP, and MPL have come onto the market much more recently. The first manufacturer of CLT based in the US was SmartLam in 2012 (SmartLam 2012); this was followed by other manufacturers that opened factories and began producing CLT panels a few years later. Among this group, arguably the most notable one was Katerra, the now infamous vertically integrated off-site construction company founded in 2015 and shut down in 2021 after filing for bankruptcy. Katerra opened a state-of-the-art CLT and glulam factory in 2019 in Spokane Valley, WA, with the largest capacity at the time and still today to produce CLT in North America (Wohlfeil 2021). This factory has since been purchased by another company and is now back in operation (Dalheim 2021).

MPP and MPL are newcomers to the family of mass timber products. They were developed and launched in 2018 and 2020, respectively, by Freres Lumber and are alternatives to CLT and glulam, respectively. Instead of using lumber boards as with CLT and glulam, MPP and MPL are produced by combining thin layers of veneer, which allows more wood to be used out of a log compared to sawn lumber. However, the manufacturing process for MPP and MPL is more energy intensive than that of CLT and glulam (Atkins 2018). At this time, MPP and MPL commercialized in the North American market—not considering the subtractive manufacturing process that turns them into custom (ETO) building components—are offered at a slightly lower price than CLT and glulam.

INDUSTRIALIZED CONSTRUCTION (IC) AND MASS TIMBER

The industrialization of manufacturing—the evolution from creating goods by hand to using machines to produce them faster, cheaper, with better quality, and in larger quantities—took place in the 1760s with the Industrial Revolution. Manufacturing has continued to evolve ever since. Ford introduced the moving assembly line to mass produce automobiles in 1913 and Toyota developed the TPS decades later, focusing on eliminating waste in its production processes and improving customer satisfaction. The construction industry, however, has lagged behind most other sectors in the adoption of technology and mechanization, which has consequently stalled productivity growth (Barbosa et al. 2017).

Various often-mentioned reasons explain why the construction industry has been traditionally slow at developing and using new technologies, and thus has not progressed at the same pace as other industries. Some of these reasons are (1) the uniqueness of every project, (2) the nature of production moving from one location to another, (3) the divided authority (owner, designer, contractor, etc.) over the process of development and construction, and (4) market volatility (Warszawski and Sangrey 1985). In recent years, however, the construction industry has increased its appetite for innovation, technology, and consequently industrialization. This is a result of owners, developers, contractors, and other players striving to become more competitive, deliver complex projects in less time, and overcome challenges such as the current construction labor shortage (Hovnanian et al. 2022).

In this context, IC has emerged as a means to leverage high-volume manufacturing principles and tools (both software and hardware) for optimizing the delivery of construction projects. Building systems and their components are designed using, for example, Design for Manufacturing and Assembly (DfMA) principles and employing digital tools, such as 3D modeling software. The fabrication of building components takes place at a location other than a project site ("off-site"), in a controlled environment (i.e., a manufacturing or factory setting). It can use Lean production principles (e.g., from the TPS) and employ mechanization or automation. The systems and components are then delivered to a jobsite, where they are assembled—i.e., connected to other parts that were either built on-site or also fabricated off-site—to create a built asset (building), which is the final product of the construction process.

Arguably the best-known IC framework at this time is the MMC definition framework, created in 2019 by the UK Government's Ministry of Housing, Communities & Local Government (MHCLG 2019). This framework presents seven MMC categories in total, of which five are off-site. Mass timber as a structural building system is part of category 3 (pre-manufacturing of non-systemized structural components), standing out as one of the most promising MMC today because of its (1) environmental benefits over alternative materials such as concrete and steel, (2) suitability for off-site automated prefabrication, and (3) easy and rapid on-site assembly.

IC and mass timber present a shift from traditional project delivery and are reshaping existing supply chains and creating new ones within the construction industry. Since large elements are fabricated off-site months or weeks before they are installed on a jobsite, intensive design efforts are required upfront. These efforts are to coordinate, integrate, and optimize structural, MEPF, and other building systems to guarantee that all key design decisions are locked in early on, before the fabrication of mass timber components begins. This ensures off-site fabrication and on-site assembly can proceed seamlessly, reducing or eliminating downstream rework.

CASE STUDY: DELIVERING A MASS TIMBER SYSTEM FOR A MULTI-STORY RESIDENTIAL BUILDING

The exploratory case study presented in this section describes the delivery process from design to installation of an ETO mass timber structural system for a multi-story affordable housing project in the US. The data for this study was collected through various unstructured and semi-structured interviews and from project documents such as construction and shop drawings and project schedules. This paper presents the initial findings of this ongoing research.

Project X herein studied is currently being delivered under a design-build contract, in which the owner signs a single contract with a general contractor who is also responsible for the design of the project. The general contractor on this project worked together with a design firm and an engineering firm to develop the architectural and structural design of the project. They also hired multiple specialty contractors to deliver the project, including Company A which was responsible for the entire mass timber scope. Company A is a vertically integrated mass timber contractor based in the US, providing design, engineering, off-site fabrication, and on-site installation services. Company A has an in-house design and engineering team and owns a fabrication facility with Computer Numerical Control (CNC) machines that are used to process FTO mass timber products (manufactured by third-party suppliers) into custom ETO mass timber components such as beams, columns, floor panels, and stairs.

For Project X, Company A's design team started to work with the architect from the beginning of the design phase. Their early involvement was crucial in the decision-making of several design, procurement, fabrication, transportation, and installation aspects of Project X's mass timber system. Designing a mass timber building requires early coordination between designers, builders, fabricators, and suppliers because mass timber components are not only long-lead items but are also fabricated off-site weeks or months before they are installed on-site. A benefit of mass timber construction is the speed at which the structure can be erected, which can shorten the project schedule, but for that to be realized it is critical that little to no rework on the mass timber components is needed after they are delivered to a jobsite.

Project X uses a post and beam structural system consisting of glulam columns and beams creating structural grids and CLT panels spanning horizontally across these grids. Most of the glulam and CLT elements in the building are exposed. Exposed MPP stairs complement the mass timber system. Steel-braced frames are used as the system to resist lateral forces, while the mass timber structure sits on top of a concrete foundation. Company A provided design and on-site installation services for the following ETO components of the mass timber system: (1) CLT floor panels, (2) glulam columns, (3) glulam beams, and (4) MPP stairs. Additionally, Company A procured FTO glulam and MPP, custom-fabricated (2), (3), and (4) at their own fabrication facility, and then delivered these elements to the jobsite, located around 170 miles from the fabrication facility. (1) were both manufactured and custom-fabricated by a third-party supplier, stored by Company A at their facility, and later delivered to the jobsite. Figure 1 depicts the major steps of delivering Project X's mass timber system, with emphasis on the design, engineering, and procurement phase.

Figure 1: Delivery Process of Project X's Mass Timber System

The design process is iterative and non-linear. Over the years, Company A has developed relationships with several architects who design mass timber structures. For Project X, Company A got involved with both the project owner and the project architect early on. Collaboratively they were able to evaluate and make design trade-offs to develop an optimal mass timber system that achieved the project goals and kept it within budget. Initial considerations included design and constructability constraints, occupancy and construction type, and project goals. After these initial considerations were understood, a conceptual design was developed, defining key project characteristics such as the number of floors, building height, building and floor areas, fire resistance ratings, and allowable exposure of mass timber. Next, Company A began to seek out potential mass timber suppliers located in North America. All suppliers for Project X were located within a 400-mile radius of the project site.

For Project X—as is the case with any multi-story mass timber building—one of the most important design decisions concerned the size of the CLT floor panels, in particular their widths.

Overall, manufacturers offer panels with the same typical thicknesses (3-, 5-, 7-, or 9-ply), but varied widths and lengths. Different manufacturers also produce CLT from different wood species, which affects the appearance of the panels (this aspect is particularly relevant when the panels are left exposed on at least one side in buildings), and have different lead times, which can severely limit the number of companies that can supply CLT panels to a project. Choosing a CLT panel supplier early in the design phase is critical because it determines what panel sizes can be used, which in turn defines the building's structural grid layout. Determining the size of CLT panels is particularly crucial because it involves three trade-offs: (1) the transportation of panels from the factory to the jobsite, (2) the number and type of surface spline joints (that are used to connect CLT panels together), and (3) the number of crane picks on the jobsite (less is better). The maximum legal load width in the US is 2.6 m (8.5 ft.), although some manufacturers can provide panels up to 3.6 m (12 ft.) wide, which could potentially reduce (2) and (3). Although most of the CLT panels used on Project X are 2.6 m (8.5 ft.) wide or narrower, some are wider than 2.6 m. The transport of oversize loads usually requires permits and can be done only during certain hours of the day (depending on local rules), which increases the cost of transportation. Determining the size of glulam columns and beams, although also important, is not so much of a constraint as it is with CLT panels. It mostly revolves around finding the most economical solution, i.e., the minimum depths and widths (lengths are determined based on CLT panel sizes) that satisfy all structural requirements, and working with suppliers that can provide those glulam elements.

One design goal of Project X, an affordable housing project that was to benefit from both a reduced project cost and accelerated installation of the mass timber system on-site, was to eliminate or reduce the number of steel connections (e.g., to connect beams to columns). Company A worked with the design team to develop a wood-to-wood mortise and tenon connection to that end. Another design goal was to have as much exposed mass timber as possible inside the residential units. To achieve that, most of the overhead MEPF systems are routed above the hallway ceilings and then distributed to each unit, so that the units could have, for the most part, fully exposed CLT ceilings.

Although Company A has an in-house engineering team that designed and engineered the entire Project X's mass timber system, Project X still had an outside structural engineer of record responsible for the engineering of the project. This engineer of record was also tasked with designing some of the structural non-mass timber components of Project X, including the concrete foundation. After the mass timber system and other related systems (e.g., lateral-load resisting, MEPF, framing) were designed and integrated, the engineer of record reviewed and signed the structural drawings. These drawings were then used to create fabrication shop drawings, where each mass timber component is individually modeled in Building Information Modeling (BIM) software. Then, files were generated to feed the CNC machines. These files describe paths for CNC machines, instructing them on how to perform the tasks required to fabricate the custom mass timber components.

Finally, after fabrication, the mass timber components were stored at Company A's fabrication facility and later delivered to the Project X jobsite when it was ready for installation. Due to space constraints on the Project X jobsite, the deliveries were JIT with all pieces being erected and put in place the same day they were delivered. Installation of all the pieces took around 8 weeks.

DISCUSSION

As new materials and products are developed and come to the market, new supply chains are formed, or existing ones are reshaped. In the case of mass timber, the supply chains to deliver these products are still emerging and worthy of research due to the growing demand for this product. Consequently, new theory and knowledge ought to be developed so that these supply chains can evolve and mature, and people can think about how to design production systems for the efficient and effective delivery of mass timber buildings.

Delivering such buildings poses new challenges when compared to delivering, for example, concrete or steel buildings. Wood requires more careful handling, storing, and transporting—for example, if a piece of mass timber is not properly stored and its moisture content is higher than ideal, it may not meet the specified tolerance requirements. Upfront design coordination is a must to ensure that all components and systems fabricated off-site not only fit together when they are brought to the jobsite but also fit with what is built on-site. Company A identified an opportunity to integrate multiple phases (design, fabrication, and installation) of the delivery process of mass timber systems and, as a result, provide their clients—owners, architects, and general contractors—with a "one-stop shop." A challenge for Company A comes from having to keep capacity across all their teams (design, fabrication, and installation) balanced (i.e., to keep all teams busy), although this has not yet been a significant issue. Demand for mass timber projects is high and increasing in the US construction market. Not many companies operate in this market space or offer the same level of vertically integrated services as Company A does, but this may change in the future as competitors seek to enter this growing market. Another challenge is that because the number of CLT suppliers in North America is still small and the current demand for the product is high, Company A does not have much bargaining power over its upstream suppliers.

From the exploratory case study presented in this paper, we present several general recommendations for teams designing or delivering mass timber systems: (1) communicate with the project owner to understand the project timeline so that it can be aligned with mass timber lead times, as they can vary from 4-6 weeks (if sourced nationally) to 3-6 months (if sourced internationally), (2) integrate design, fabrication, and installation by having the design team coordinating with the fabrication and installation teams so that all fabrication and installation constraints can be understood early enough to reduce design iterations and facilitate fabrication and installation, (3) before locking in the grid layout and consequently the panel layout of a building, find out what products and sizes mass timber manufacturers offer and then design accordingly to optimize the use of CLT panels since it accounts for most of the volume (70 to 85%) of mass timber in a multi-story building, (4) standardize by reducing the number of unique mass timber connections to speed up and reduce complexity in design (less detailing), fabrication, and installation, (5) evaluate ways to reduce the number of MEPF penetrations through floors and beams by, for example, strategically using corridors (with soffits) and shafts to distribute MEPF systems, and (6) verify and reconcile the tolerance of mass timber components with other off-site and on-site building components during design of the mass timber system.

CONCLUSION

The aim of this paper was twofold: (1) to describe the characteristics of the mass timber supply chain and (2) to describe the process of designing and delivering a mass timber structural system for a multi-story building. To achieve (1), we presented mass timber construction as an MMC, a number of mass timber products and their respective applications, and how the mass timber supply chain has developed in North America. To achieve (2), we presented an exploratory case study, described the major steps in designing and delivering a mass timber structural system for a multi-story residential building, and presented a list of recommendations for designing and delivering mass timber systems.

Some future research ideas stem from the limitations of this exploratory case study. This paper provides only a general view of the delivery process of a mass timber system. Additional research is needed to develop more detailed process maps (e.g., value stream maps), focusing, for example, on other phases (e.g., fabrication) of the mass timber delivery process to identify additional opportunities for improvement. Furthermore, research is needed to study other types of mass timber projects (e.g., commercial- or educational projects) and compare their characteristics with the (residential) case study presented in this paper. In addition, future research could also investigate opportunities to use other IC building systems that in conjunction with mass timber can accelerate the delivery of construction projects.

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LEAN AND IOT INTEGRATION TO IMPROVE FLOW IN CONSTRUCTION PREFABRICATION: A PROPOSED FRAMEWORK

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ABSTRACT

Creating a stable and smooth flow is an essential principle of lean thinking. Failure to create a stable flow in the production system degrades performance and impacts value creation. In construction prefabricated systems, variability in flow between the construction site and manufacturing plant can cause an increase in time and cost of the projects. This paper aims to deal with the problem of lack of synchronization between the onsite and offsite fabrication. To achieve this aim, a framework that is based on the integration between lean and the Internet of Things (IoT) is proposed. The proposed framework integrates the planning and control work from the Last Planner System® (LPS) with IoT to improve the planning, tracking, and delivery of prefabricated components. The study sheds the light on some of the expected challenges that may face the use of the proposed framework and covers the preliminary observations after putting it in use to improve flow in the delivery of prefabricated steel components.

KEYWORDS

Lean construction, Last Planner System® (LPS), Internet of things (IoT), lean construction 4.0, construction prefabrication, flow.

INTRODUCTION

Construction prefabrication is the term that describes the practice of producing a certain quantity of building components partially or fully in a factory to further assembly on the construction site (Qi et al., 2021). As one of the most important examples of industrialization of construction (Cheng et al., 2023), construction prefabrication has attracted attention and is considered an effective way to improve performance in the Architecture, Engineering, and

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Construction (AEC) industry. This is due to the various improvements it could improve when it is compared with conventional on-site construction practices (Cheng et al., 2023; Xu et al., 2018). Examples of possible improvements include time and cost savings, reduction in greenhouse gas emissions (GHGs), safety improvement, reduction in materials consumption, and productivity gain (Arashpour et al., 2015; Mossman & Sarhan, 2021; Qi et al., 2021; Xu et al., 2018). Prefabrication is also an effective way to reduce more than half of the physical waste (Jaillon et al., 2009). While comparing fully on-site construction with prefabrication, Horman et al (2006) presented a list of economic, social, and environmental benefits of prefabrication. Some of these benefits were the establishment of long-term supply chain planning, less maintenance work and reworks due to the improved quality, fewer defects, variety in materials choices, improved de-constructability, and improved working conditions.

Nevertheless, prefabrication in projects faces various challenges that may hinder the smooth flow of processes. According to Mossman and Sarhan (2021), synchronizing flow between offsite prefabrication and onsite construction is essential to ensure success when depending on prefabricated components. This synchronization has to cover all flow phases starting from the arrival of the raw materials at the factory and ending with the onsite assembly. Failure to achieve such synchronization can prohibit the delivery of materials or components and cause an increase in time and cost of the project (Kanai et al., 2021). The heavy dependence on the critical path method (CPM), delivery of materials based on pushing strategies, and lack of focus on optimizing the overall production system in the factory and site are among the most affecting factors that limit the flow synchronization (Mossman & Sarhan, 2021). The use of lean principles and tools such as the Last Planner System® (LPS), Jus-In-Time (JIT), and Kanban or pull signals can help mitigate the impact of these problems by focusing on the end-to-end process flow, collaboratively working and planning based-on what can be done rather than what should be done, and produce and deliver only what is needed and when it is needed (Kanai et al., 2021; Mossman & Sarhan, 2021).

The Internet of things (IoT) has shown effectiveness in managing the flow of information and materials in many sectors but has still not been adopted on a large scale in the construction industry. IoT can help in reducing the time between data capture and decision-making, which allows for coping with real-time changes in the production system (Ben-Daya et al., 2019). It also helps improve coordination and facilitates monitoring based on accurate information. Furthermore, it helps to identify the locations and track employees, trucks, and materials, which result in higher productivity and safer site (Gamil et al., 2020; Kumar & Shoghli, 2018; Matteo Giovanardi et al., 2021). Its interaction with lean comes from its ability to improve the visualization of processes and share it with different stakeholders to improve flow, collaboration, problem-solving, error-proofing, and achieving continuous improvement (Dave et al., 2016; Tezel et al., 2022). Therefore, there have been, recently, various efforts to support lean-IoT integration. These efforts have resulted in some lean-IoT applications and software such as Visilean®, KanBIM™, and others (Dave et al., 2016; Kanai et al., 2021; Sacks et al., 2011). Nevertheless, the focus on synchronizing flow between offsite and onsite operations and integrating LPS planning results in this synchronization is still not widely implemented. The current study proposes a lean-IoT framework to integrate LPS planning levels in the synchronization between the construction site and the prefabrication factory.

LITERATURE REVIEW

PROCESS DEFINITION AND TECHNOLOGY USE IN PREFABRICATED CONSTRUCTION

The literature has several definitions for the prefabrication process. For instance, Cheng et al (2023) considered that the process can be depicted in three main stages such as design, manufacturing, and onsite assembly. According to Liu et al (2020), the process comprises ordering, manufacturing, transportation, and assembly. In turn, Qi et al (2021) stated that the prefabrication process includes design and planning, production and manufacturing, delivery and store, and the assembly stages. In their study, Qi et al (2021) affirmed that challenges along all these phases can appear. The traditional approaches, which consider mainly architectural and performance requirements in the design stage can lead to a decrease the efficiency; therefore, manufacturing, delivery, and assembly aspects have to be considered. In the production stage, the lack of real-time information to monitor quality, location, and performance aspects can hinder optimal productivity. In the delivery process, errors in logistic management can affect the performance of the whole project.

Cheng et al (2023) classified technologies in offsite construction (OSC) based on data perspective technologies into data acquisition, data integration, data analysis, and decision-making technologies. For the acquisition, their study listed paper-based monitor and sensor techniques. They highlighted the use of long-range radio communication techniques (LoRA), radio frequency identification (RFID), the global positioning system (GPS), laser scanning, and photogrammetry techniques. The integration technologies connect data with web platforms. In the making decision field, most of the decisions are taken by human actors and some are taken by artificial artifacts. Liu et al (2020) found in their review, advances in the management and implementation levels for OSC. In the management process, strategic research, overall design, and supply chain integration and management are key. At the technological level, supply chain process design and optimization and application of advanced technology.

TECHNOLOGICAL GAPS AND CHALLENGES IN PREFABRICATED CONSTRUCTION

According to Xu et al (2018), despite the numerous expected benefits when presenting technological solutions to construction prefabrication companies, these companies face various challenges. Among these challenges, is the reliance on traditional methods and the resistance to adopting new technologies, which results in inaccurate and inefficient practices. The second problem is the low level of coordination and collaboration, which prohibits the dissemination and sharing of information with the prefabricated companies; as a result, causes late and misplaced delivery. The third problem is related to the nature of the prefabricated companies as most of these companies are small and medium-sized companies (SMEs). It is widely conceived that this type of company faces several challenges when trying to adopt technology such as the lack of financial capabilities, lack of managerial flexibility, resistance to change, lack of skilled employees, and lack of knowledge (Agostini & Nosella, 2020; Albalkhy et al., 2021; Albalkhy & Sweis, 2021; Elhusseiny & Crispim, 2022; Kolla et al., 2019). The fourth problem is that most of the provided technology-based practices do not fully address the nature of the prefabricated construction and the link between the onsite and offsite production in construction. As a result, these solutions cannot be directly applied in prefabricated companies (Xu et al., 2018). Additionally, in their review, Qi et al (2021) classified the technologies that are currently applied in prefabricated construction into business digitalization, computer-integrated design, data acquisition, optimization, predictive analytics, and robotics and automation. According to their analysis, most technological applications to improve prefabrication processes have been done in a research context.

Based on the above-mentioned challenges, more practical and scalable technologically supported solutions should be proposed and put into use. However, these technologies should fit with the nature of work in the prefabricated construction sector. They also should ensure high levels of collaboration between different stakeholders in the project and synchronization of practices and flow on the site and at the factory. This means that the proposed frameworks should be based on linking the three pillars of production systems, which are technology, process, and people. Linking these pillars is essential in lean thinking (Sacks et al., 2010).

THE PROPOSED FRAMEWORK

The current study is based on linking planning and control deliverables of the construction processes with the manufacturing processes in the prefabricated companies to ensure the synchronization of flow processes between the two production systems. To do so, the proposed framework tries to cover deliverables from the planning and control tool (LPS), application of JIT and pull signals, and development of IoT architecture to continuously track, monitor, and localize prefabricated components. The proposed framework was based on studying different cases in offsite and onsite construction (Chen et al., 2020; Dave et al., 2016; Kanai et al., 2021; Li et al., 2018; Von Heyl & Teizer, 2017; Xu et al., 2018) and based on studying a process map in a prefabrication company in Canada.

LAST PLANNER SYSTEM® (LPS)

LPS is one of the most important tools that support the adoption of lean theory in the construction sector (Albalkhy & Sweis, 2022). LPS can be understood as a short-term planning tool that is based on integrating collaborative planning with all possible stakeholders especially the last planner (people who do the work) (Ballard, 2000; Mossman & Sarhan, 2021). As shown in Figure 1, LPS has generally different levels of planning and control and incorporates the pull concept and plan based on what "CAN" be done instead of the push mechanism that is based only on what "SHOULD" be done. This planning structure identifies constraints to be removed, develops performance measures such as Planned-Percent-Completed (PPC), and integrates the learning process based on the principles of continuous improvement and non-compliance to plan analysis (Porwal et al., 2010). The main planning and control levels in LPS are (LCI Congress, 2016):

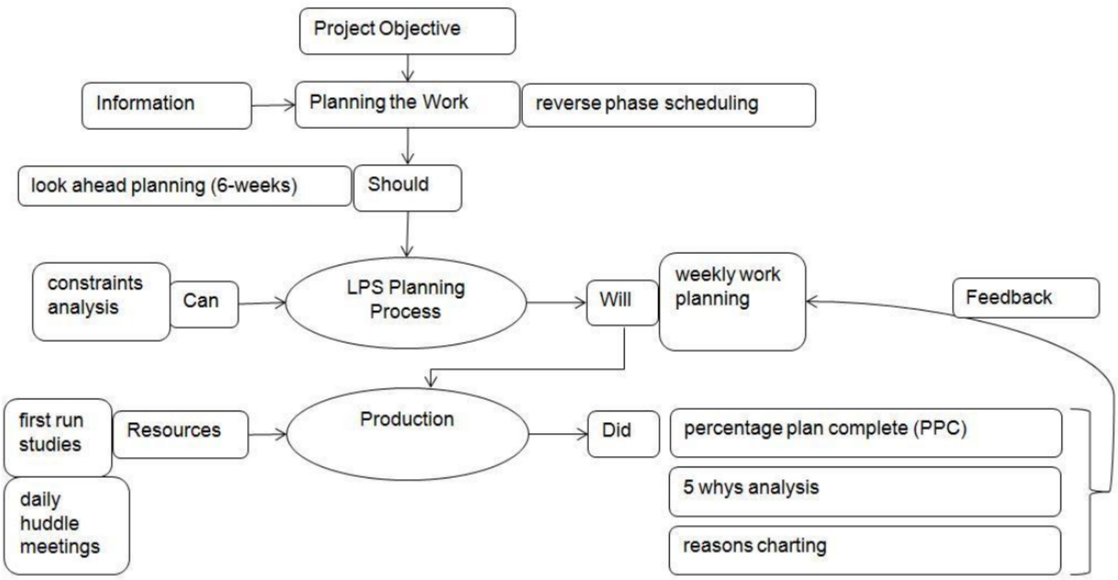

Figure 1: LPS planning process (Porwal et al., 2010).

1- Master planning or milestone planning: which defines the overall road and the main milestones of the projects (identifying what should be done).
2- Phase planning or pull planning: collaborative planning of phases to achieve the milestones (identifying what should be done).
3- Lookahead planning: uses phase planning to make work ready. In this phase, the focus is on identifying constraints-free tasks (identifying what can be done).
4- Weekly work plan (WWP): a detailed weekly plan that includes commitments and promises to deliver the tasks (identifying what will be done).

5- Daily huddle meetings and learning: to identify what will be completed and what was completed, what needs to be re-planned, and how to prevent deviations from the plan (identifying what will be done and what was done).

According to Mossman and Sarhan (2021), the short-term collaborative planning approach in LPS facilitates the synchronization of flow between onsite and offsite fabrication and creates the conditions for JIT delivery, which aims to reduce the volume in inventory and ensure the delivery of materials to the right place at the right time. With a technological application such as Building Information Modeling (BIM) and IoT, LPS planning can integrate real-time information that can create reliable flow, improve visibility, and reduce variability (Dave et al., 2016; Mossman & Sarhan, 2021; Sacks et al., 2010).

IOT-BASED ARCHITECTURE FOR THE PROPOSED FRAMEWORK

According to the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) (ISO/IEC, 2014), IoT is "an infrastructure of interconnected entities, people, systems and information resources together with services which process and react to information from the physical world and from the virtual world".

Figure 2 shows the various layers of the IoT architecture in the proposed framework inspired from (Karmaoui et al., 2022; Rankohi et al., 2023). The developed architecture is based on using barcode tags, RFID antennas, and readers for collecting data. The data transmission is done by WiFi to databases that are accessible to the plant operators and project managers to conduct analysis and make decisions. As shown, the proposed architecture consists of three main layers: perception, network, and application layers.

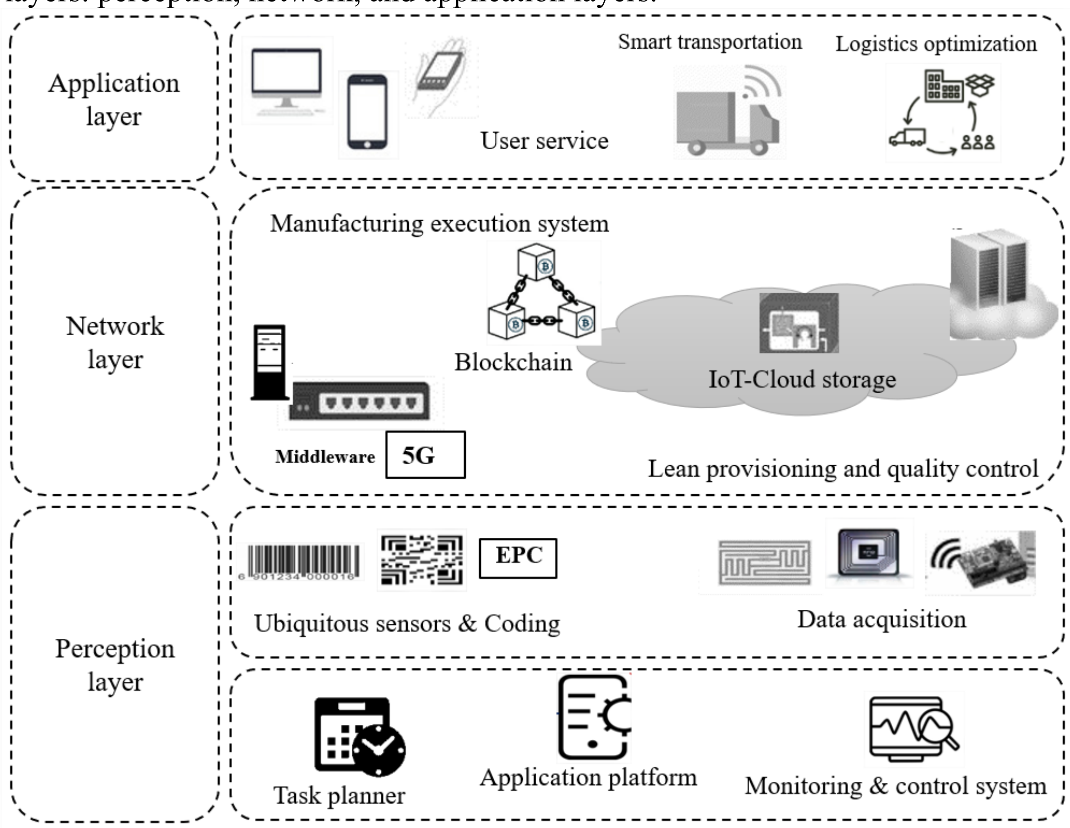

Figure 2: IoT-based architecture for the proposed framework.

The perception layer represents platforms for planning the tasks, using the application, and monitoring and controlling systems. It also represents units that are responsible for coding, information extracting, data processing, controlling, and monitoring. In the coding phase, an ID number is assigned to each prefabricated component. The component can be recognized in the whole cycle of the IoT. Then, the obtained information will be transmitted from the collection phase in the perception layer to the lean analyzing phase in the network layer. The network layer is a network platform based on IPV6. It consists of an intelligent network, which connects all the resources in the network. In this layer, data is collected and objects are identified via RFID tags. Then the information is integrated into the cloud, to manage and control the collected data in real-time. In this layer, the data is reorganized, filtered, shared, and transformed into the content service in the Service-oriented architecture (SOA).

Finally, the application layer integrates the service capabilities and provides the application service to the clients. Users can use different applications to access their required information, such as smart transportation, smart material tracking, and logistics optimization. For instance, barcodes are installed on prefabricated components. The users can use a smart material tracking application to scan these barcodes with their smartphones, which directs them to any used storage (e.g. company's database or website). This application can be equipped with mobile tag reader technologies, which are used by the clients to make sure they have collected all received steel bars in returning racks. In addition, clients can use this application to send automated alerts to project managers to inform them that prefabricated components or pallets are ready for pick-up.

PROCESS

Figure 3 shows the process in the proposed framework. The proposed framework covers the different phases of the prefabrication process and the onsite and offsite fabrication. It also integrates different LPS levels with the IoT tracking system for the delivery and installation of prefabricated components. The framework is integrating the pull concept, buffering, and JIT during the production and manufacturing and delivery, and storage phases. It is also linked with nD BIM models to improve the tracking of the process flow.

More specifically, the process starts with the development of the master planning, which is the first level of LPS planning. At this level, the main milestones of the project are identified and the development of the BIM models starts. The next phase is the phase or pull planning, in which the supplier of the prefabricated elements should participate and define the estimated lead times to deliver the orders. Using the results from the pull planning, the requirements and orders can be estimated and the look-ahead plans can be developed.

Estimates of the orders and requirements are useful to identify the production schedule and initiate the production process of the elements to be stored in warehouses. Simultaneously, the work on site focuses on the identification and removal of all possible constraints that may hinder the installation of the prefabricated elements onsite using logs from the look-ahead plans. Following the identification and removal of constraints, onsite demands and transportation plans are created to deliver the elements on time to the site. Based on the transportation plan, elements can be pulled from warehouses to be tagged and identified in the IoT system. The trucks can be tagged and linked to the IoT system as well.

The IoT system is responsible for delivering real-time updates about the delivery process including tracking, localizing, and counting the delivered elements and reporting any problem that may happen. Once the elements arrive at the site, they can be directly integrated with the weekly work plans, then installed, and then integrated into the daily huddle meetings and learning sessions.

Despite the potentials of the proposed framework, it is worth mentioning that there are different points to consider when integrating lean construction and IoT. Examples of these points include the security of data, availability of skills and knowledge when implementing the proposed framework, availability of policies and guidelines for implementation, connectivity, in addition to acceptability and readiness to make a change in the traditional practices (Albalkhy & Sweis, 2021; Khurshid et al., 2023).

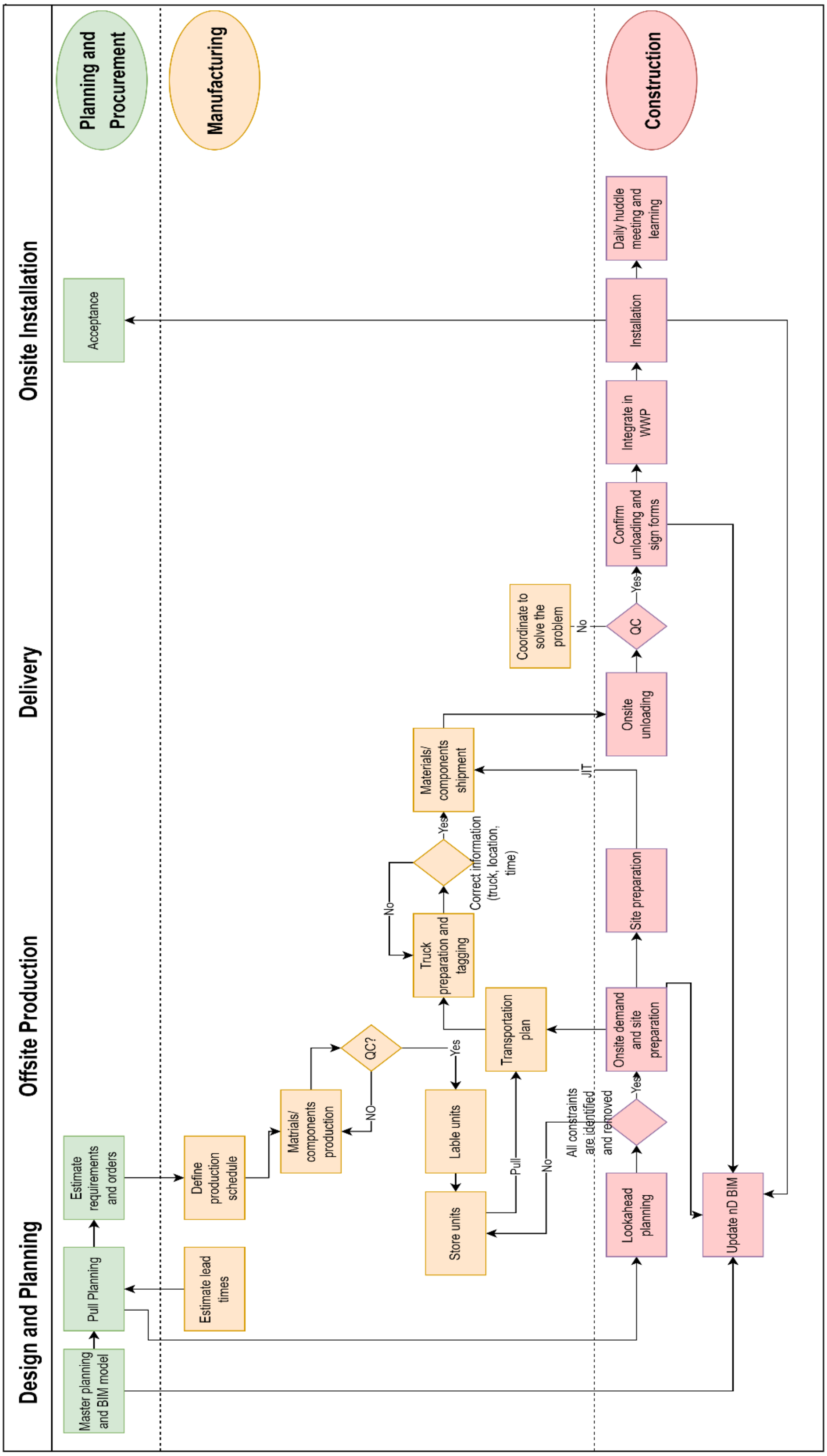

Figure 3: The proposed framework.

CONCLUSIONS AND FUTURE DIRECTIONS

The proposed framework was presented to improve the flow of prefabricated components and avoid the problems of lack of synchronization between the onsite and offsite fabrication. Integrating the plans from LPS and IoT in the proposed framework can help to improve the efficiency of prefabricated delivery. This is due to improving the traceability, localization, and identification of these components, enhancing the communication between the plant and the site, and avoiding errors resulting from the low levels of coordination. The proposed framework can be effective in linking the supplier schedule and the production plan of the project, which is very helpful to achieve improvement along the whole process rather than achieving fragmented changes that might not result in time reduction, cost saving, or quality improvement. Moreover, the proposed framework aims to reduce flow variability, cope with complexity, increase flexibility, and improve the decision-making process in prefabricated construction.

The proposed framework is to be tested to deliver construction prefabricated steel components in a Canadian company. The preliminary experiments utilizing the proposed IoT-based platform show initial promising results concerning the ability to track the delivery and installation of steel components. Nevertheless, despite starting the implementation of the framework, its results are not yet evaluated and validated. Therefore, further extensive experimental studies on-site and in manufacturing plant environments are required to validate the proposed framework. In addition to conducting more cases, future work can be conducted to identify possibilities of framework improvement using, for instance, digital twin technology to improve on-time tracking and monitoring and artificial intelligence (AI) to predict delivery dates. Further research can also focus on studying different performance indicators for the proposed framework or different barriers to adopting it.

The current study aims to contribute to the existing efforts to link lean construction and construction 4.0 practices (known as lean construction 4.0). It also serves as a good example to integrate both concepts to improve the performance in offsite and modular construction.

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MATURITY MODELS IN OFF-SITE CONSTRUCTION AND ANALYSIS OF LEAN INCORPORATION: REVIEW

Jesús Ortega[1], Alejandro Vásquez-Hernández[2], Harrison A. Mesa[3], and Luis Fernando Alarcón[4]

ABSTRACT

The adoption of off-site construction (OSC) is still uncertain although many contributions to its promotion have been made. In many studies, lean construction (LC) has been declared to be the most suitable approach to support managing OSC, but there are challenges regarding its incorporation into OSC. A maturity model (MM) has been proposed to evaluate and guide OSC adoption. However, the literature shows misunderstandings about the MM structure and how these models incorporate LC. This article aims to review maturity models (MMs) developed in the OSC field to identify benefits and deliver deep insight into their structure and the incorporation of LC. The methodology involved three steps: *(i)* systematic literature review (SLR) of OSC-MMs, *(ii)* thematic analysis to identify associations among MM benefits, OSC barriers, and LC challenges, and *(iii)* analysis and interpretation of results. The findings suggest that MMs developed in OSC are incipient, many of them suffer bias and have weaknesses in their structure, and LC incorporation is poor and not explicit in most OSC-MMs.

KEYWORDS

Off-site construction, prefabrication, lean construction, maturity models, barriers.

INTRODUCTION

Off-site construction (OSC) is an innovative type of construction that has been demonstrated to be more effective in overcoming the inefficiencies associated with traditional construction (Suliman & Rankin, 2021). OSC is also known as off-site production, industrialized construction, concrete prefabricated housing, and modern method of construction (Blismas et al., 2010; Dang et al., 2020; Liu et al., 2018; Wang et al., 2020). All these terms refer to innovative engineering systems in which significant portions of operations and construction elements are produced off-site in a factory environment before the final assembly on-site (Suliman & Rankin, 2021). The benefits of OSC adoption are related to improving quality, productivity, and safety, reducing labor intensiveness and construction time, and ensuring better

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sustainable performance (Dang et al., 2020; Suliman & Rankin, 2021; Wang et al., 2020). Despite all these advantages, the adoption of OSC still faces significant resistance (Nadim & Goulding, 2011), particularly in developing countries where adoption remains low (Dang et al., 2020). Previous studies have identified several OSC barriers that inhibit its adoption. In the current research, OSC barriers identified in the context of the Chilean architecture, engineering, and construction (AEC) industry are used as the main reference. According to Ortega (2022), low OSC adoption, to some extent, is attributed to the inability to objectively evaluate the benefits offered by OSC due to a lack of knowledge, technical skills, and experience related to this type of construction. In addition, all these challenges are enhanced in an AEC industry that is characterized by conservative behavior, in which innovative systems such as OSC seem to be a risk that many organizations do not need to assume.

In sum, OSC suffers from the ineffectiveness of successful measures to improve its project performance for organizations and a lack of adequate understanding of the system to understand the current level of adoption of the organization and how to improve it (Dang et al., 2020).

LEAN IN OFF-SITE CONSTRUCTION

The OSC approach differs from conventional construction methods (Bendi et al., 2021) in many aspects, such as the complexity of the buildings, manufacturing process, application of technologies, logistics system, planning, coordination, and control. This can be explained by the similarities between OSC and the manufacturing approach (Höök & Stehn, 2008). Therefore, the AEC industry must be prepared to adopt suitable manufacturing practices and be prepared to change old practices to enable this to happen (Mawdesley & Long, 2002). To this end, lean construction (LC) is a philosophy conceptualized at the beginning of the 1990s that came from the Toyota production system and aimed to meet the client's requirements (deliver value to customers). Comparable to OSC, lean construction is also an innovation in the AEC industry (Singh & Kumar, 2020) and is based on adapting manufacturing practices to construction. For this reason, LC has been mentioned in many studies as the most suitable approach to support the adoption of OSC.

The effectiveness of LC principles in OSC projects has been proven. Mawdesley & Long (2002) researched two case studies. All the projects involved the provision of multistory office blocks, and a different procurement system was adopted for each case. In the first case, a traditional procurement method and conventional practices were employed in the construction phase. In the second case, a lean approach, which consists mainly of the early incorporation of all stakeholders before the start of the design phase, was used. The results showed up to 98.3% improvement in factory productivity, a 50% reduction in on-site operations, and a 180% increase in on-site efficiency against the traditional procurement method (case Study I). Other studies have made positive alterations to the OSC production system to make improvements and implement lean tools. For example, Yu et al. (2013) implemented 5s, standardized work, takt time planning, variation management, and value stream mapping in a shelter production line. In only 6 months of implementation, significant improvements were achieved, including a 34% increase in labor productivity, a reduction in overtime of 15% of total man-hours, and a reduction of 15% to 2% in average staff and personnel absenteeism.

Notably, benefits for the AEC industry can be obtained in a short time by using OSC and LC together. However, empirical evidence highlights that it is not enough to just move to a factory environment to institute lean culture because OSC exhibits a project-based culture and the production setup, construction site, and temporary organization are similar to traditional construction (Stehn & Höök, 2008). Therefore, most implementations within LC in OSC are fragmented. Furthermore, there are still challenges that inhibit the adoption of LC, including complexities in understanding it, lack of strategies for implementing LC at the micro level (downstream players), and lack of guidelines for gradually introducing LC to the construction industry (Aslam et al., 2020). Addressing these issues might support a successful start to incorporating LC into OSC and the effective adoption of OSC in the AEC industry.

MATURITY MODELS AND OPPORTUNITIES

Maturity models (MMs) seem to be an ideal methodological tool for addressing the aforementioned concerns. MMs may facilitate OSC adoption and alleviate the challenges of clarifying LC incorporation into OSC. Since the introduction of MMs in the software manufacturing industry (Wang et al., 2020), MMs have been used in different fields (e.g., medical service, science, technology, and the manufacturing sector). MMs are used to assess the maturity of elements in the process to determine the maturity level reached by the system (Cano et al., 2020). In addition, this tool provides benchmarks (the current organization level), highlights paths to reach excellence (maturity gaps), and identifies goals or target levels (Suliman & Rankin, 2021). Consequently, several studies have employed MMs to assess the maturity of new technology implementations or strategies in the AEC industry (Razkenari & Kibert, 2022).

In sum, MMs deliver several benefits for organizations. For example, they enable organizations to know their ecosystem in terms of performance status, current capabilities, and what they need to achieve organizational goals by supporting the development of better management practices. Furthermore, this application makes it possible to reduce the competitiveness gap among construction firms and to deliver a differentiated, sustainable, and innovative value offer (Cano et al., 2020). All these arguments support the idea that configuring an MM based on LC as a suitable approach to achieve the requirements of OSC may mitigate the key barriers that inhibit OSC adoption and the challenges for the incorporation of LC.

This article aims to review the existing MMs in OSC to identify the potential benefits and determine the current structural gaps, the thematic areas they address, and the incorporation of the LC approach. In doing so, the paper has three specific objectives: *(i)* identify the benefits of MMs and their relationship to address the challenges that inhibit OSC adoption and the incorporation of LC into OSC; *(ii)* assess of the MMs that have been developed in the OSC field; and *(iii)* explore the potential research opportunities of OSC-MMs development through the systematic incorporation of LC into OSC.

METHODOLOGY

The primary method used in the current research is a systematic literature review (SLR). The methodological framework involved three principal stages: *(i)* systematic literature review of MMs in OSC, *(ii)* thematic analysis of MM benefits, OSC barriers and challenges to incorporating LC into the OSC field, and *(iii)* analysis and interpretation of the selected OSC-MMs. Figure 1 presents the entire research process.

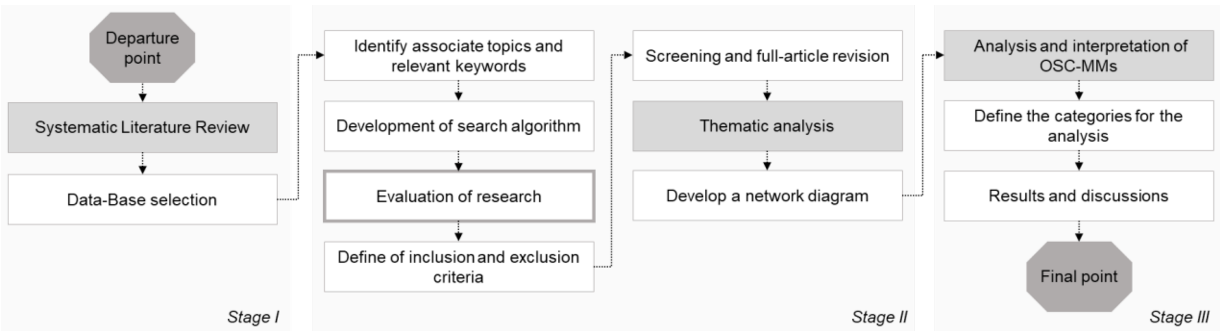

Figure 1: Research frameworks

STAGE I · SYSTEMATIC LITERATURE REVIEW

The SLR methodology is an objective, replicable and transparent tool that is used to examine the existing studies on a subject (Levy & Ellis, 2006). Furthermore, SLR has been used in the AEC industry to *(i)* establish the boundaries of existing research, *(ii)* identify potential future research considerations, and *(iii)* keep up-to-date with developments on a subject (Ibrahim Y. Wuni, Shen, & Osei-Kyei, 2019). Therefore, the authors adopted SLR because it helps organize and compile suitable studies to obtain information of interest and determine the main coinciding characteristics among them. The SLR approach comprised selecting the database, identifying the associated topics and relevant keywords, developing the search algorithm, defining inclusion and exclusion criteria, and evaluating the research.

Database, topics and keywords, and algorithm development

Once the research objective(s) was established, database selection was the next step in the SLR. According to Donthu et al. (2021), settling on one appropriate database is recommended to mitigate the need to consolidate information into a single format and minimize potential human errors. Therefore, the SLR was performed in Scopus, given the recommendations by other studies in the field of OSC construction management (Ibrahim Y. Wuni, Shen, & Mahmud, 2019). Moreover, Scopus has been mentioned as the research engine that covers more journals and recent publications than any other database (Aghaei Chadegani et al., 2013; Ibrahim Yahaya Wuni & Shen, 2020).

Next, a list of keywords was identified in the extant literature. This list comprised synonyms of “Off-site construction” and “maturity model”. Then, to ensure coverage and to develop the search algorithm, the ‘title/abstract/keyword’ functionality of Scopus and the Boolean concatenator ‘OR & AND’ were used. The search algorithm contained the following: (“off site construction” OR “off-site construction” OR “offsite construction” OR “modular construction” OR “modular integrated construction” OR “prefabricated prefinished volumetric construction” OR “modern method of construction” OR “prefabrication” OR “prefabricated building” OR “industrialized building system” OR “industrialized building” OR “industrialized housing” OR “industrialization” OR “industrialised construction” OR “industrialised housing” OR “industrialisation”) AND (“construction”) AND (“maturity Model” OR “maturity” OR “model capability” OR “maturity grid”). The search was restricted to papers published between 2010 and 2022 and articles in the English language because it is the most widely used scientific language (Ibrahim Yahaya Wuni & Shen, 2020). In the end, 49 studies were retrieved.

Evaluation research: Inclusion and exclusion criteria

Inclusion and exclusion criteria were established to ensure that the retrieved research studies met the quality requirements (Ibrahim Yahaya Wuni & Shen, 2020). According to Tranfield et al. (2003), this step is relatively subjective and, to avoid any bias should be performed by more than one reviewer. Thus, two researchers with experience in OSC and MMs participated in this step. The main inclusion criteria involved *(i)* articles that develop a type of maturity model under the topic of OSC and *(ii)* articles that are published in a peer-reviewed journal or rated conference proceeding.

Screening and full-article revision

Based on the algorithm developed and inclusion/exclusion criteria, the authors screened the titles and abstracts of the 49 articles, which resulted in the inclusion of 10 articles. A duplicate check of the 10 items was performed, and no duplicates were found. Then, a full-text evaluation was employed, and a final list of 8 articles was included for further analysis and interpretation. The search was repeated before submission to ensure that important recently published articles were included in the study. No articles were added to the final sample. Figure 2 depicts the screening process through a flowchart.

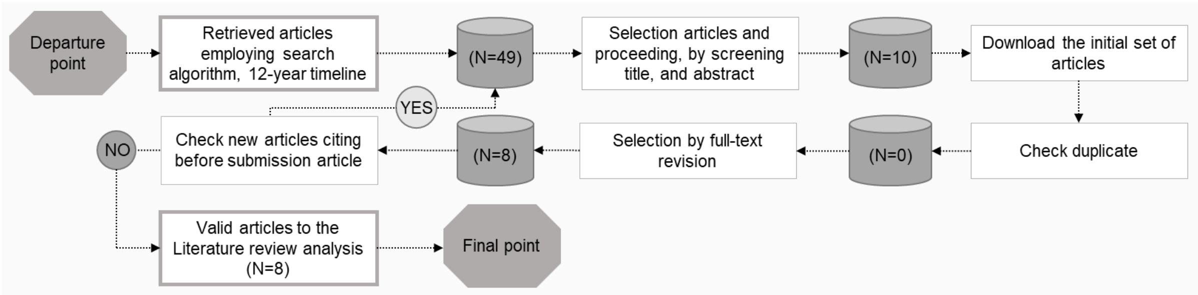

Figure 2: Article protocol selection

This stage was concluded with a complementary literature review to identify other benefits of MMs beyond those of the previously reported OSC-MMs and challenges prevailing in incorporating LC into OSC. The topics in Scopus included "LC challenge in OSC," "barriers to implementing LC," and "maturity model in construction." The OSC barriers were mainly taken from those identified in the Chilean AEC industry context by Ortega (2022) and from the articles chosen in the SLR.

STAGE II · THEMATIC ANALYSIS

A thematic analysis was employed to identify in the literature the aspects regarding how the benefits of MMs can contribute to overcoming the barriers that inhibit OSC adoption and the incorporation of LC. Thematic analysis is a method that is used to identify, analyze, and report patterns (themes) within records (Braun & Clarke, 2006). To this end, the authors summarized and codified the most relevant benefits of MMs reported in the literature, mainly in the OSC field, and listed the fundamental OSC barriers and challenges that must be addressed to facilitate OSC adoption and the incorporation of LC into OSC. Then, a network diagram was built, wherein the nodes at the bottom represent the MMs benefits, and the nodes at the top represent the OSC barriers and LC challenges. Finally, the patterns among those variables were represented with arrows. This input supports the author's idea that MMs are a powerful tool that must be developed in the OSC field to help and facilitate its adoption.

STAGE III · ANALYSIS AND INTERPRETATION

Stage III aimed to extract the relevant evidence from the final list of articles to support the analysis and interpretation of each OSC-MM. According to Broome (1993), to analyze and interpret information, each study that forms part of the literature review needs to be categorized, ordered, and summarized. Therefore, the authors established 6 categories for the analysis. If any article did not contain information in a category or subcategory, the label "no information" was employed. Table 1 shows the name and description of each category.

Table 1: Categories employed in the analysis and interpretation of OSC-MMs

Category	Subcategories	Description
Geospatial contribution	Article's location	Region or country in which the paper was developed.
	Publication's year	Year in which the article is available to the readers.
Maturity measure	Maturity levels	The scale is employed to measure the maturity level.
	Descriptors	Name of each maturity level.
Application areas	-	It is related to the dimensions targeted by the maturity model.
Analysis method	Qualitative (Qlt)	No weighting mathematical or statistical method is applied.
	Quantitative (Qnt)	A mathematical or statistical method is applied.

Weighting method	-	Approach to assigning value for dimensions or indicators that comprises the maturity model.
Lean construction adoption	Low level = "**0**"	LC adoption is low or imperceptible. Not explicitly stated by the author.
	Medium level = "**+**"	LC adoption is palpable. It does not necessarily have to be made explicit by the author.
	High-level = "**++**"	LC adoption is remarkable. The author explicitly states it.

RESULTS

Table 2 shows MMs' main benefits as a methodological tool. The review was conducted in the construction field, and special attention was given to the OSC area. The outcome was the identification of 11 benefits of MMs. Regarding OSC barriers and LC challenges, the authors detected six key (6) OSC barriers and four (4) LC challenges that can be effectively addressed by applying an MM base to incorporate lean construction into OSC.

Table 2: MMs benefits, OSC barriers, and challenges for the incorporation of LC within OSC

Item	ID	Description	Reference
MMs Benefits	MMb1	Allows identifying weak areas or gaps	[1] [2] [3]
	MMb2	Serves as a prescriptive tool for improving performance	[1] [2] [5] [13]
	MMb3	It is a tool to assess an organization's maturity (e.g., process maturity, product maturity, the skill of people, social system) and to assist in increased maturity level	[1] [2] [3] [4] [5] [6] [9] [13]
	MMb4	Assists in continuing improvement	[2] [3] [6] [7]
	MMb5	Helps managers to reach organizational or project goals	[1] [2] [6] [10] [13]
	MMb6	Helps to set prioritized goals	[1] [6]
	MMb7	Serves to assess the maturity of new technologies in the AEC industry	[6]
	MMb8	Helps to reduce the competitiveness gap among organizations	[10]
	MMb9	Promotes the creation of value	[10]
	MMb10	Serves as a comparative tool (e.g., benchmarks tool)	[1]
	MMb11	Establishes a common and shared language	[8]
OSC barriers	OSC1	Lack of understanding of manufacturing principles to be applied in OSC	[5] Cf. [9]
	OSC2	Lack of market maturity	[1] [3] Cf. [9]
	OSC3	Failures in the management of OSC projects	Cf. [9]
	OSC4	Insufficient project management skills	[9]
	OSC5	Poor project performance	[5]
	OSC6	Inability to assess the benefits offered by OSC	[9]
LC Challenges	LC1	Complexities in understanding LC	[11]
	LC2	Lack of appropriate lean technology or tools	[12]
	LC3	Lack of strategies to implement LC	[11]
	LC4	Lack of guidelines for introducing LC gradually into the industry	[11]

Note: **[1]** Suliman & Rankin (2021) **[2]** Wang et al. (2020) **[3]** Liu et al. (2018) **[4]** Wei et al. (2022) **[5]** Dang et al. (2020) **[6]** Razkenari & Kibert (2022) **[7]** Bendi et al. (2021) **[8]** Blismas et al. (2010) **[9]** Ortega (2022) **[10]** Cano et al. (2020) **[11]** Aslam et al. (2020) **[12]** Yuan et al. (2020) **[13]** Correia et al. (2017)

Following Table 2, through a network diagram, Figure 3 indicates the direct relationship between MM benefits and key OSC barriers and LC challenges. Almost five positive MM benefits would have an impact of mitigating one OSC barrier and one LC challenge at the same time. The benefits of MMs have addressed the overall key OSC barriers and LC challenges. This result suggested that MMs are a powerful tool for facilitating the adoption of OSC, especially in mitigating key OSC barriers that have been reported recently in developing countries.

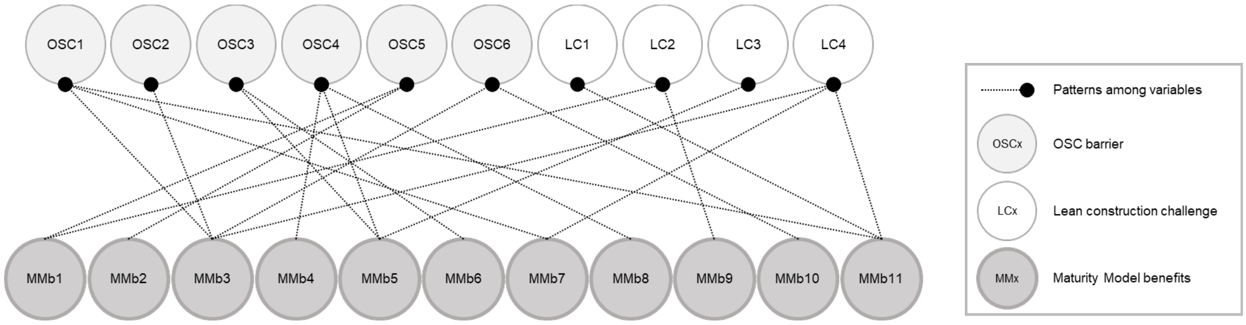

Figure 3: Benefits of MMs to overcome OSC barriers and challenges of LC incorporation.

ANALYSIS AND INTERPRETATION OF OSC-MMS

This section summarizes the SLR findings of the OSC-MMs identified. The results respond to the analysis and interpretation based on the categories established in stage III.

Geospatial contribution of MMs in the OSC field

Despite the potential positive impact of MMs on overcoming OSC barriers and LC challenges, as suggested in Figure 3, the geospatial contribution in the domain of MMs (Table 3) indicated a low level of development of this methodological tool in the field of OSC. Just only 8 OSC-MMs have been developed in the last twelve years. Moreover, every country and region has its realities, and many dimensions in the OSC field require doc treatment. Furthermore, it is not possible to establish a statistical trend in the development of MMs in the field of OSC over time. However, in the last 3 years, the authors observed an incipient development of this methodological tool of 2 MMs per year worldwide.

Table 3: Number of papers per year and geospatial contribution.

Location of development	Year												
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
International													1
Canada												1	1
India												1	
China									1		2		
Australia	1												

Structural key categories of OSC-MMs

The authors ordered the key categories that comprised OSC-MMs in Table 4. These categories support the inference that there is no unique way to build up MMs in OSC. For example, regarding maturity measures, some OSC-MMs comprise 3, 4, or 5 maturity levels. Additionally, most of them used different terminologies to describe each maturity level. Even one "MM" in the sample did not employ a descriptor for the maturity levels. The relevant contribution of maturity levels is clearly describing the path to reaching higher maturity levels. However, the findings suggested that not all authors gave a full explanation. These outcomes correspond to those of reviews carried out in other construction areas, e.g., sustainability (Correia et al., 2017).

Table 4: Key categories that constituted OSC-MMs

ID	Levels	Descriptors	Application areas	Analysis Method		Weighting Method	LC adoption
				Qlt	Qnt		
[1]	5	1.Limited 2.Promising 3.Adopted 4.Implemented 5.Accepted	Technology and engineering methods	✔	✔	No information	+
[2]	4	1.Initial 2.Upgraded 3.Integrated 4.Optimal	Enablers: leadership, participants' capabilities and collaboration, planning, and control, technology and schema Results: product, society, organization, management, and control	✔	✔	Analytic Hierarchy Process (AHP)	+
[3]	5	No information	The procurement process, operation efficiency, relationship coordination and strategy alignment, and corporate social responsibility	✔	✔	No information	+
[4]	5	1.Initial 2.Repeatable 3.Defined 4.Managed 5.Optimized	Data Structure, Data Inflow, Virtual Twin Modeling/Decision-Making, Data Outflow	✔	✔	No information	+
[5]	5	1.Very low 2.Low 3.General 4.Good 5.Very good	Technology, operation management, sustainable construction, and economic	✔	✔	Fuzzy Analytical Hierarchy Process (FAHP)	+
[6]	4	1.Explore 2.Initiate 3.Control 4.Optimize	Technological, functional, and organizational components	✔	✔	No information	+
[7]	3	1.Low 2.Medium 3.High	Operational challenges, broad execution strategy, planning certainty, and operational efficiency	✔		No information	+
[8]	-	No information	Cooperative innovations in prefabrication	✔		No information	+

ID= Identification of the research authors corresponds to the same ID used in Table 2.
LC adoption: Low level = "0," Medium level = "+," High-level = "++".

Regarding "application areas," the scope of MMs is variable. Researchers focused on a particular area of interest, which can be at the level of process or product, e.g., technological capabilities, operation management, procurement process, construction sustainability, or the product's design-production-logistic-maintenance. Most MMs for the analysis method included both quantitative and qualitative approaches. This approach helps to provide mathematical measurements of the maturity assessment and an in-depth understanding of each level. However, no consensus or standard concerning the weighting method applied in MMs exists. Therefore, even most MMs did not include this approach. The weighting method refers to the criteria for assigning a value to each dimension and indicator that was used to build each MM. This helps determine the preponderance of one application area over another (cf. Wang et al., 2020), and the intention is to eliminate the difficulty in obtaining practical data and the subjective nature of expert evaluation (Dang et al., 2020). A few studies have employed the analytic hierarchy process (AHP) or fuzzy analytic hierarchy process (FAHP) to evaluate MMs.

The evaluation outcomes related to LC adoption are aligned with expectations due to similarities between OSC and LC. All studies, to some extent, present management practices or tools belonging to LC. For instance, various studies have established the adoption of BIM, virtual design, or simulation as a minimum standard for incorporating OSC. Additionally, the early integration of the value chain to develop an integrated design and construction is also considered an initial maturity level in OSC adoption. More than half of MMs (e.g., [2], [3], [5], [6], [8]) include explicit mentions of LC to make a comparison with some of their own concepts or just to encourage its use. For example, training the workforce based on lean concepts is recommended to facilitate the improvement in production and construction in situ (Razkenari & Kibert, 2022). However, what should be learned, how, and when is not explicit. In other words, there is no clear explanation of how to implement LC in those MMs that promote its use.

DISCUSSION

MMs have certain limitations. For some MMs, a scale of maturity level or maturity level descriptors was not developed. Instead, applying qualitative analysis methods was the only focus, making it difficult to generate numerical indicators to assess maturity. For a few, a weighting method for the framework's dimensions and indicators was adopted. This suggests that most of the MMs had a significant degree of subjectivity and bias.

In most studies, the incorporation of LC in the dimensions/indicators of the OSC-MMs must be inferred. Consequently, determining the objectives and functionalities of LC practices and tools in the MMs frameworks is not provided. Therefore, the challenges of “complexities in understanding LC” (LC1) and “lack of appropriate lean technology or tools” (LC2) are not resolved. In contrast, this lack reinforces these challenges since it sets off a critical ambiguity space due to the variety of terms that are often used to explain the same concept and assumptions that must be made to select the appropriate LC practice/tool. For example, the transportation component is conceptualized regarding the assurance and efficiency of component transportation, considering distances, storage, and availability. This is associated with LC's “just in time” (JIT) management practice, which could have been standardized under this term. Such a divergence of terms contributes to a “lack of understanding of manufacturing principles to be applied in OSC” (OSC1). This scenario in a sector that is characterized by being conservative and volatile promotes the entrenchment of the known (e.g., traditional construction practices). It, therefore, transfers old vices to the OSC field.

Creation value-oriented management is an essential characteristic of the LC approach (Koskela, 1992). An important finding is that none of the OSC-MMs presented performs a *value analysis* regarding the dimensions that comprise each MM framework. Most of the proposed dimensions are taken from the literature, interviews, or workshops but do not have a *value analysis* to guarantee that the proposed dimensions meet internal (organization) and external (customers) requirements. Therefore, a vital principle of LC is not considered in the confection of MMs.

CONCLUSIONS

In this research, an SLR of the MMs developed in the OSC field using the Scopus database was conducted, and the level of LC incorporation in those OSC-MMs was evaluated. The literature review results showed poor development of this approach in the OSC field. Only 8 OSC-MMs have been developed in the last 12 years in a few countries. Furthermore, the incorporation of

LC showed weaknesses in terms of establishing a common language, providing clarity in the applications of LC practices and tools, and conducting an explicit and integrated framework for the adoption of LC. The authors identified that the OSC-MMs comprise transversal dimensions across the AEC industry at the global and local levels since each region has different "financial and market conditions" and "policies and regulations." This scenario confirms the idea of the poor availability of OSC-MMs. Moreover, the network diagram highlights how MM benefits can positively impact overcoming key barriers that inhibit OSC adoption. Therefore, the use of a powerful tool to facilitate OSC assessment, measurement, and adoption is lacking.

The analysis showed that application areas addressed by MMs are diverse and not directly associated with OSC phases in most cases. Based on this, the authors found the need to promote the development of OSC-MMs from two perspectives: *(i)* considering the project life cycle and *(ii)* using LC as a main approach to avoid any room for ambiguity. In addition, the authors suggest that in future developments of OSC-MMs, a *value analysis* of their dimensions/indicators should be performed as a complementary method of validating the model.

Despite its contribution, the study has certain limitations. The review includes research articles or proceedings. Other types of documents in which a kind of MM could have been developed to measure OSC maturity were not considered. Although some researchers recommend using one database, the authors suggest that a more extensive review, including other recognized databases in the scientific field, must be employed. Additionally, this paper mainly focused on exposing the weaknesses regarding incorporating LC into OSC-MMs. Therefore, future research should develop a comprehensive review of the LC critical coincident factors that have been included in the current MMs. This will be a baseline for further OSC-MMs development and facilitate incorporating LC practices or tools. Nevertheless, future revisions can take the current revision as a starting point to address the stated limitations.

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DEVELOPING A FRAMEWORK FOR ASSESSING TEAM ALIGNMENT IN CONSTRUCTION USING TVD

Nazanin Najafizadeh[1] and Farook Hamzeh[2]

ABSTRACT

Customers’ value is crucial to the success of a construction project, and team alignment is required to steer projects toward their intended value. Alignment is when the right people work together on a project to generate and achieve values that are consistently communicated and accepted. In the architecture, engineering, and building industry, teamwork challenges are inevitable. The existence of a team does not guarantee the success of the project, and a dysfunctional team might result in project failure, wasting resources such as time, money, and energy. Target value design (TVD) is a lean approach that leads the design and construction phases to meet project objectives while adhering to team and project limits. Based on their values, each project has different conditions, facts, or impacts that help strengthen team alignment (factors). Additionally, a team that is aligned has particular qualities that are recognized as attributes. Measuring and assessing team performance based on TVD using factors is complex. This research fills the gap in the literature review concerning the measurement and assessment of team alignment. The process and its results could help construction project leaders regularly assess and identify team strengths and weaknesses to improve team alignment. A case study is also presented to apply the proposed framework to measure team alignment on a construction project, to improve team performance.

KEYWORDS

Lean construction, target value design, collaboration, and team alignment.

INTRODUCTION

The architectural engineering and construction (AEC) sectors require a cooperative effort that has become more multi-disciplinary, complex, and interconnected (Ashcraft, 2016). There are various challenges in setting up a virtual organization for building projects. The AEC industry's long history of individualism and hostility is the first obstacle. Instead of working in teams, people have worked together on projects in groups. Furthermore, due to the casual usage of the term "team" many individuals mistakenly assume they have participated in teamwork (Ashcraft, 2011). In order to transform groups into teams, there must be a substantial shift in how people collaborate and in how work and hierarchy are organized. In a software environment, it is said that "successful deployment of multifunctional teams involves a radical rethink of the whole firm" (Larman, 2008). The lack of collaboration between designers, subcontractors, and other specialized groups as well as the unpredictability of costs, timelines, and quality standards

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during the design phase reports that typically come after those from the construction phase are the causes of disappointments. The result is costly rework, change orders, and repricing, which is off-target for clients (De Melo et al., 2016).

Target value design (TVD), a lean approach technique for creating value in projects with favorable features, has also been acknowledged by Miron et al. (2015). The cornerstones of effective TVD implementation are team alignment (TA) and value alignment (VA) (Ashcraft, 2016). By leveraging the client's perceived value as a design engineer and attempting to minimize waste, or at least surpassing the client's expectations, TVD is also used to improve cooperation (Kim & Lee, 2010). When TVD is not used, poor team alignment (TA) creates several obstacles and problems that ultimately cause projects to fail (Griffith, 2001). According to the literature study, little to no research has been done on utilizing TVD to measure and evaluate TA.

Based on the ideas from TVD, this study aims to propose a framework to measure team alignment in construction projects. The measuring technique used to assess the framework through relationships and correlations between team alignment attributes and factors is a quantifiable variable that is influenced by these interactions. This study's industrial contributions include showing how to employ a team alignment measurement tool to assess team performance in AEC projects and offering analyses with a roadmap for identifying team weaknesses and improvement possibilities. Pearson’s correlation coefficient test and the Fuzzy Inference System (FIS) are two approaches used in the experiment to simulate correlation and measurement. Participants completed the prepared survey, and data analysis techniques were then applied to the survey findings. Based on the findings, suggestions are made for improving team alignment.

PREVIOUS RESEARCH

Lean project delivery system is a form of integrated project delivery (Mossman et al., 2013). Lean construction or lean project delivery is the process of applying lean thinking to the conception and execution of capital projects, or the delivery of projects in general (de Melo et al., 2016). Lean projects are arbitrary production processes that offer products with the highest possible value and the least amount of waste. The main differences between standard and lean project delivery are the stages, interactions between phases, and participation in each phase (Ballard & Howell, 2003).

The goal of target value design (TVD), a Lean management practice and design methodology, is to provide customer value while adhering to a project's restrictions (Kaushik & Koskela, 2015; de Melo et al., 2016). TVD was developed based on the principles of target costing used in the manufacturing industry, but with modifications to its ideas, methods, and implementations. This approach is an upgraded version of target costing that emphasizes the creation of stakeholder value as a driver for design and construction. While target pricing concentrates on setting "cost" goals, target value design extends this concept to include targets for time, quality, and value, among other factors. Since its inception in 2002, TVD has gained popularity and acceptance among construction firms in the United States, according to Do et al. (2014). TVD successfully minimizes cost overruns and maintains predictable project costs, delivering projects for up to 20% less than market value without compromising quality or schedule; ensures early participation of key stakeholders; and promotes collaboration (Do et al., 2014).

Team alignment and value alignment are prerequisites of TVD. “Organizations develop alliances, often termed networks or constellations, to match their own goals with stakeholders' interests and to decrease environmental uncertainty,” according to Barringer and Harrison (2000). The condition in which team members collaborate within acceptable bounds to create and realize consistently specified and accepted project values can be characterized as the alignment between appropriate project participants (Griffith, 2001). Even if groups operate differently, they can still align if they share the same objective. The project's outcomes are directly impacted by the project team's alignment. These direct ties also looked into the possibility that alignment mediates the connections between the project's antecedents and outcomes (Griffith, 2001). According to Frey et al., 2006, three primary categories for partnerships categorized based on the level of alignment, which ranges from low to elevated are misaligned (networking and cooperation), poorly aligned (coordination and coalition), and aligned (collaboration and alignment).

The fragmentation of the company's specialized teams causes a lack of alignment between team members and project stakeholders, as noted by Ashcraft (2011). This misalignment can result in leaders wasting time pursuing productive ideas that are not the most important goals at the time, according to Kochhar (2013). Moreover, if the company's culture is unclear to operational employees, they may lose trust in its vision, objectives, and value proposition, which can impede their willingness to give their best to the project, leading to a negative impact on the company's culture and bottom line. In contrast, strategically linked firms are more effective and deliver better results because team members work together to achieve common goals and objectives (Ashcraft, 2011). When people are not strategically linked, they may become confused about their priorities, make fewer effective decisions, and engage in conflicts, which can lead to a lack of excitement and motivation to do their best work. Therefore, people want to be part of something meaningful.

The current study aims to evaluate team alignment and its impact on project success by examining several factors such as the level of commitment to the team and project value, morale among team members, ability to overcome challenges, and providing timely and creative knowledge and information. Table 1 presents the research studies focusing on implementing TVD, team alignment, and influential factors for promoting team alignment. However, none of them have proposed a method and framework to measure team alignment based on TVD.

Table 1: Implementing TVD to Evaluate Team Collaboration

Researcher	Research topic
Musa, 2019	A framework for implementing target value delivery to enhance value creation in the construction industry
Griffith, A. F, 2001	Team alignment during pre-project planning of capital facilities
Do et al., 2014	Alignment and misalignment of commercial incentives in IPD and TVD
Ismail et al., 2014	Developing a framework of metrics to assess collaboration in IPD
Che Ibrahim et al., 2013	Development of a conceptual team integration performance index for alliance projects

METHODOLOGY

Design science research (DSR) is the approach followed in this study. According to Hevner et al. (2007), DSR strives to learn about and comprehend a problem area by developing and deploying a designed artifact. The basis for adopting design science as a research method is the purpose of DSR, which has been stated as creating trustworthy information to be utilized in designing solutions to problems and significantly advancing the practice and theory of the subject in which it is employed (De Melo, 2015).

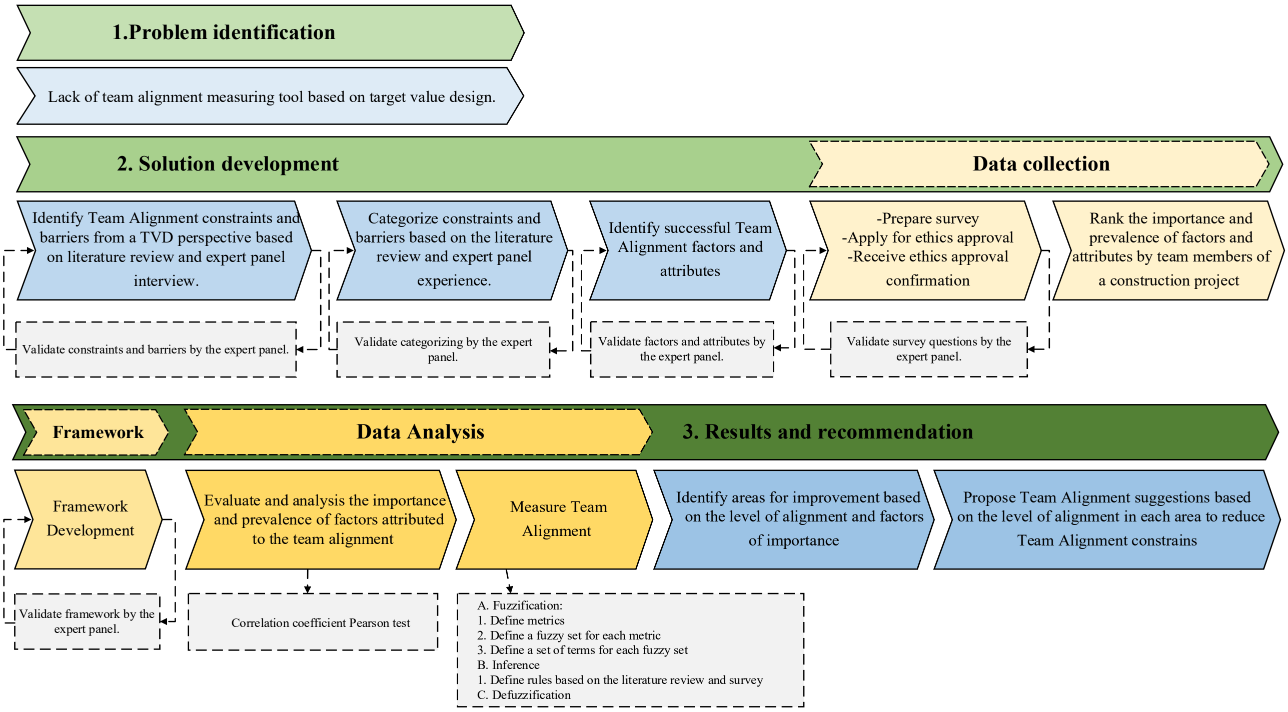

Figure 1: Research Methodology

The three major phases of this research are problem identification, solution development, results, and recommendation. Figure 1 illustrates the approach employed in the study.

Problem Identification

Project failures will result from any issues or deficiencies in the catching value during project phases. Consequently, delivering value will be aided by a regular review of the team's TVD performance. Understanding team alignment drivers and impediments can help project leaders improve and prepare for new challenges. According to the literature study, a team alignment tool built on the target value design principles is required. Leaders can discover the team's strengths and shortcomings by continuously analyzing and measuring team alignment.

Solution Development

The three stages of solution development are as follows. Starting with the TVD principles, it identifies team alignment limitations, impediments, factors, and attributes. The creation of a framework is the second step. Data gathering is the next stage of the solution creation process. The following sections provide explanations of the steps listed.

Team alignment challenges from a TVD perspective

The first step in bridging a gap is to thoroughly understand it from all angles. TA difficulties are known in the solution development phase based on the literature study and are confirmed by the expert panel. This research was developed based on the TA challenges in the literature review. The fishbone diagram (Figure 2) presents a root cause analysis and five main categories of challenges that hinder team alignment in TVD implementation. The major groups include personal characteristics, training, management, culture, and environment.

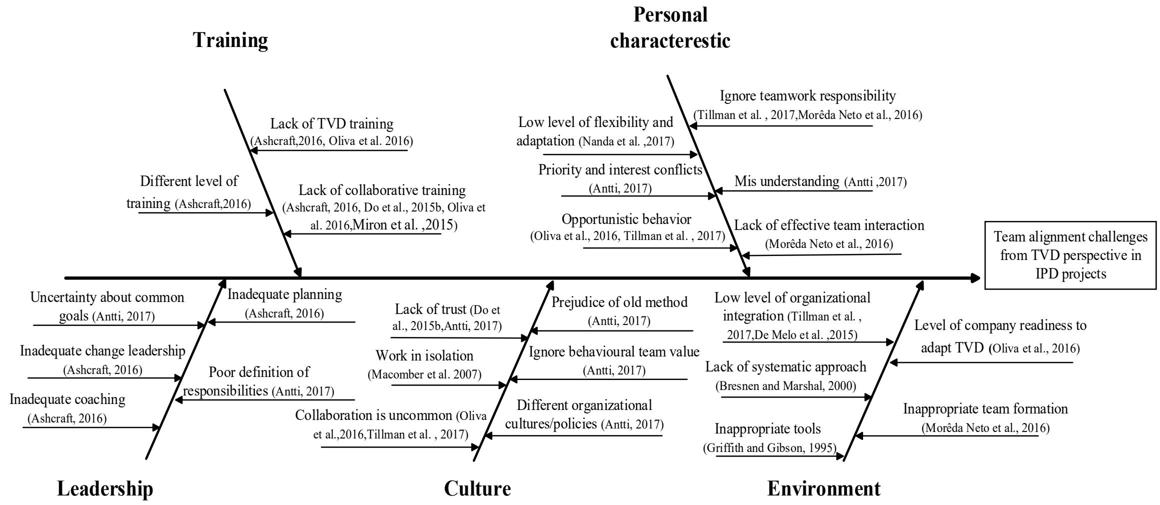

Figure 2: Team Alignment Challenges from TVD Perspective in Construction Projects

IDENTIFY SUCCESSFUL TEAM ALIGNMENT FACTORS AND ATTRIBUTES IN TVD

Being a qualitatively abstract concept, alignment means different things to different teams and projects. The attributes of an aligned team will be what distinguish it. Team leaders and members determine these traits based on the values of the team and the project. To meet the demands of the available cross-functional and multidisciplinary construction teams, these features are multifaceted in the building project. Based on the TVD principles from the literature, this research has compiled a list of factors and attributes for effective team alignment which 24 factors and 5 attributes were verified by the case study team lead. The values, knowledge, or circumstances that support team alignment are contained in factors. The most influential factors may be improved by construction team leaders by being aware of them, assessing them, and investing time and resources into improving them (Table 2).

Table 2: Research Successful Team Alignment Proposed Factors

No.	Factors descriptions	No.	Factors description
F1	Team members have good problem-solving and decision-making skills.	**F13**	Leaders assign tasks that fit team members' strengths and capabilities.
F2	Team members listen effectively and empathize with each other. They share constructive feedback transparently.	**F14**	The team members' strengths and weaknesses are regularly assessed by management.
F3	Team members trust each other to speak up-phycological safety.	**F15**	The project scope and value are clearly defined by team leaders and communicated visually.
F4	The team learns about each other's past professional project collaboration experience.	**F16**	Leaders and team members know and understand the risks and rewards of the project on which they are working.
F5	Team members are encouraged to work on the project.	**F17**	A collaborative culture exists among team members.
F6	The team focuses on the project's goals and objectives.	**F18**	Members respect the teams' diversity; accept and treat each other fairly and equally. Diversity, Equity, and Inclusion (DEI).
F7	Team members are knowledgeable and are constantly trained to work on IPD projects and use Lean techniques and TVD.	**F19**	Leaders and team members express and apply innovative ideas to projects.
F8	Team members benefit from training approaches and methods.	**F20**	Team members attend face-to-face meetings in the big room.
F9	Team members are trained in effective and frequent communication.	**F21**	Members come from different educational and professional backgrounds.
F10	Team leaders ensure that members have equal access to information, equipment, and technology.	**F22**	Leaders size their teams properly according to the project's workload, size, and nature.
F11	Lean mentors are available to guide and train team leaders.	**F23**	Leaders and team members are satisfied with their collaboration and hope to continue it.
F12	Team leaders collaborate with other cross-functional teams and provide cross-disciplinary expertise for successful communication.	**F24**	Key participants are involved early in the project.

Team alignment attributes are qualities or characteristics that are thought to be a component of the alignment (Table 3). Factors are the causes and conditions that enable team alignment, while attributes are the characteristics of an aligned team. Therefore, team alignment factors and attributes are distinct concepts.

Table 3: Successful Team Alignment Attributes

Attribute no.	Attribute description
AT1	Level of commitment to the team and project value
AT2	Level of morale among team members
AT3	Ability to overcome challenges
AT4	Provide the right knowledge and information at the right time
AT5	Level of creativity

DATA COLLECTION

The purpose of the survey is to assess the validity of team alignment factors and attributes as well as their importance and prevalence. Prevalence is the present degree of evaluation of factors and qualities in the team project, whereas importance indicates the priority of factors and attributes as well as the predicted value for the team. Prevalence might fluctuate often with each update or new evaluation, although importance can have a more or less constant value in this context. The Likert scale, a non-comparative, one-dimensional scaling method consisting of 5 points, was utilized in this study, with 1 representing the least prevalent or important factor and 5 representing the most prevalent and significant factor. The expert panel employed the Likert scale in this study's validation phase to rate various factors and attributes.

RESULTS AND RECOMMENDATIONS

The last phase is results and recommendations that start with the framework (Figure 3) development, continue with data analysis, and end with the team performance improvement proposal.

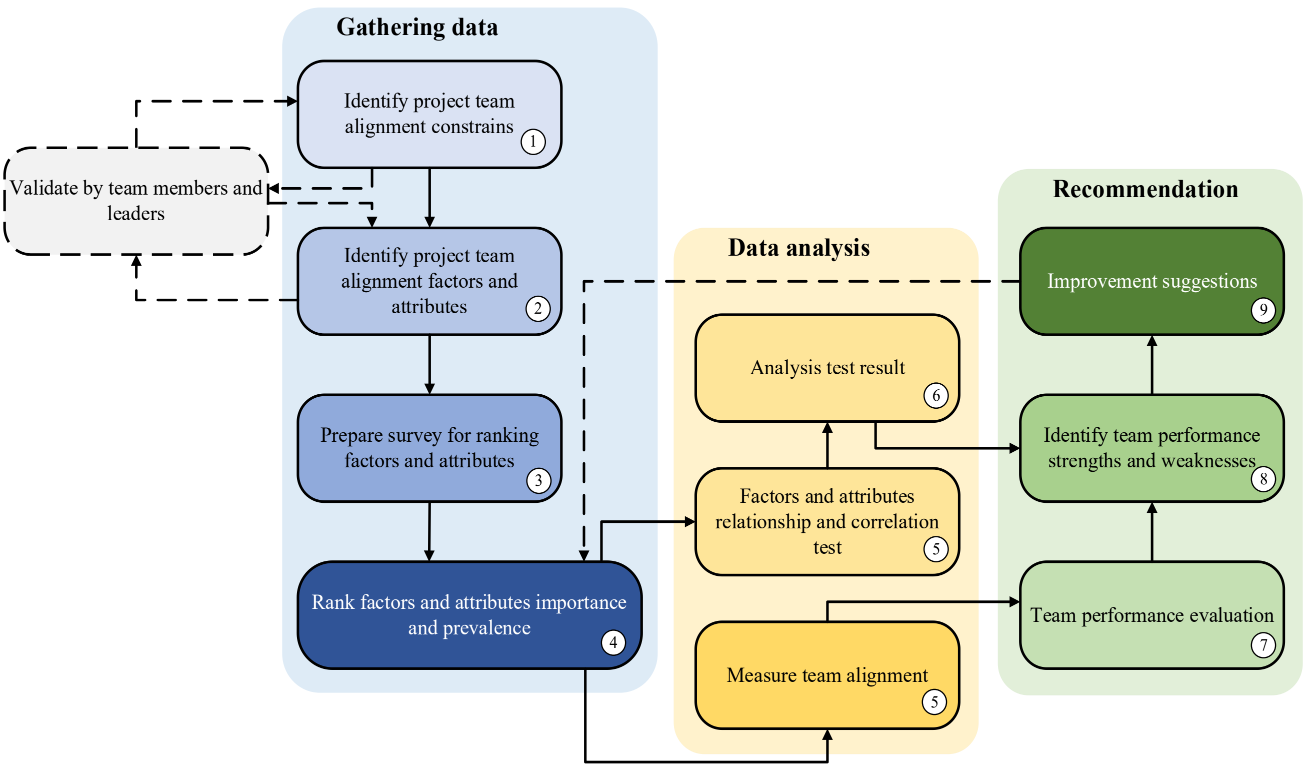

Figure 3: Team Alignment Measuring Framework

The method of developing the framework is innovative and is based on current scientific understanding and real-world experience with construction projects. The proposed framework consists of three phases which are gathering data, data analysis, and recommendation. The concept is built on the connection and correlation between team alignment, factors, and attributes (Figure 4). The Correlation coefficient Pearson's test is used to identify the correlations and coefficients between factors and attributes.

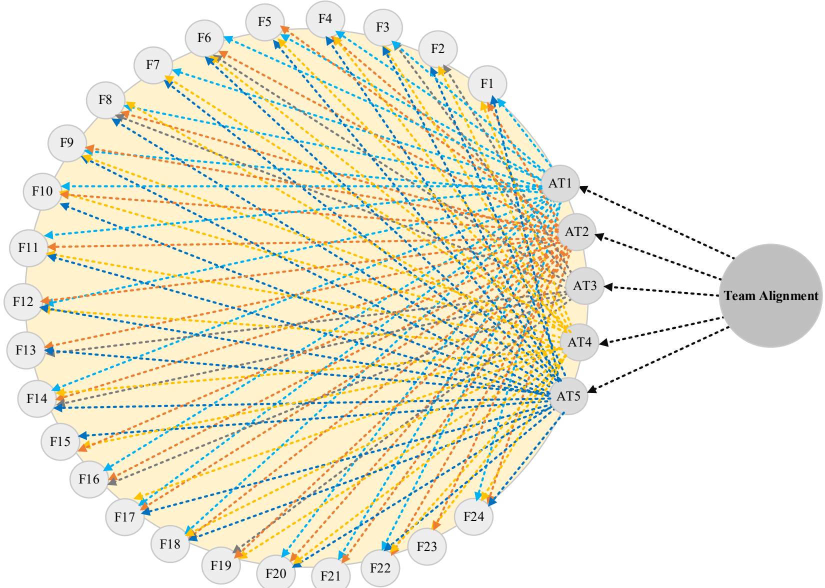

Figure 4: Research Assumptions

Team alignment is a qualitative quality that is subjective and cannot be quantified using quantitative techniques. To address this, our study models the interactions between factors and attributes using fuzzy inference systems (FIS). As mentioned in the data collection section, we ranked the team alignment attributes prevalence in the team project, and the ranking results were used in the FIS to convert a qualitative ranking to a quantitative measure. After measuring each attribute in the FIS, we identified the related factors based on the Pearson correlation coefficient test results. The comparison between attribute prevalence and importance measures helps team leaders identify critical attributes that need improvement. The value of attribute importance represents attribute vitality, and the gap between attribute importance and prevalence indicates the attribute's critical situation. Reaching the level of attribute importance should be the team's feature goal. The correlation test results identify the factors related to these critical attributes for improvement so that team members can focus on them. The recommendation section will provide guidelines based on the effective factors related to critical attributes.

RESULTS AND DISCUSSION

This research offers a method for assessing team performance and keeping track of team alignment on construction projects. This framework attempts to monitor team members' advancement and performance in accordance with the team, project, and corporate values. The method may be used for construction projects, and depending on the project value, influential elements, and aligned team qualities can be identified for each project. It will help team leaders pinpoint the group's strengths and weaknesses and establish monthly and yearly objectives to boost output. A case study of an IPD project at a construction business is used in this study to evaluate the framework.

The survey questions were created, validated with the project manager for the case study, and approved by the University of Alberta's ethics committee before being sent to the project team. The case study is a New Mechanical Wastewater Treatment Plant that is located in Lloydminster, Alberta, Canada. The research required data collected from case study project team members. Out of the 20 members of the project team, 18 participated in the survey to rate the prevalence and relevance of various elements and traits using a Likert scale.

According to FIS's analysis of the attribute's prevalence rating, the case study's team alignment measurement will be 81.2 percent. Although the team is cohesive, there is still potential for development. When team members set the target value too low, they will not be able to increase team performance and will not benefit from this framework. This number fluctuates from project to project depending on the relevance of the characteristic that team members specify by their rating. Team members likely require additional training on lean principles, target value delivery, and team alignment if they give the team alignment traits a low-priority ranking.

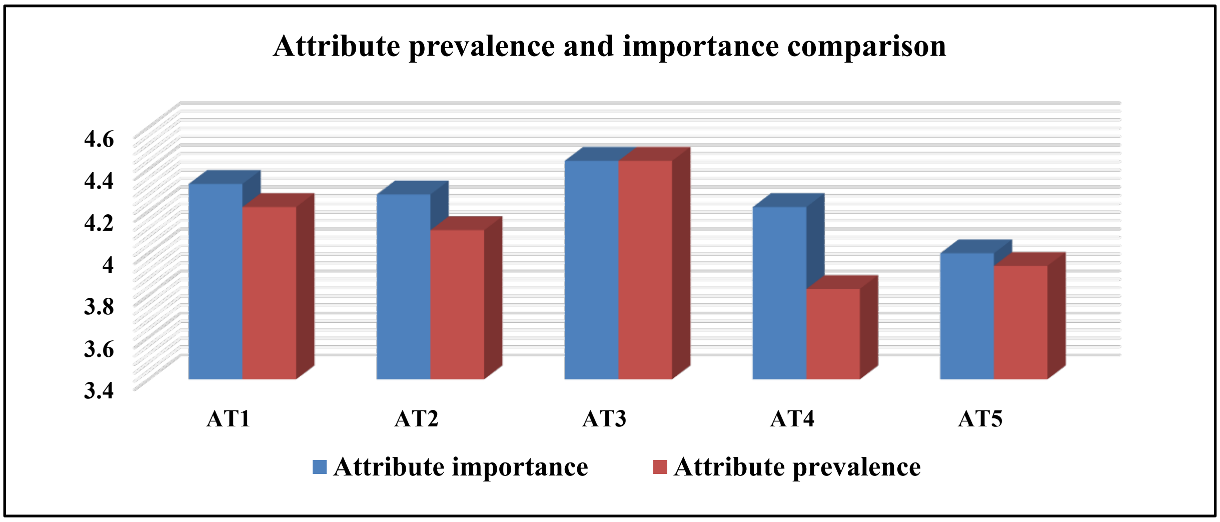

Figure 5: Factors Correlate Values Based on Attributes for Survey Result

Figure 5 compares the mean importance and prevalence of the qualities. Except for attribute four (providing the appropriate knowledge and information at the appropriate time), the mean difference between the importance and prevalence of each attribute is less than 0.2. A larger disparity between importance and prevalence indicates a critical situation for the attribute.

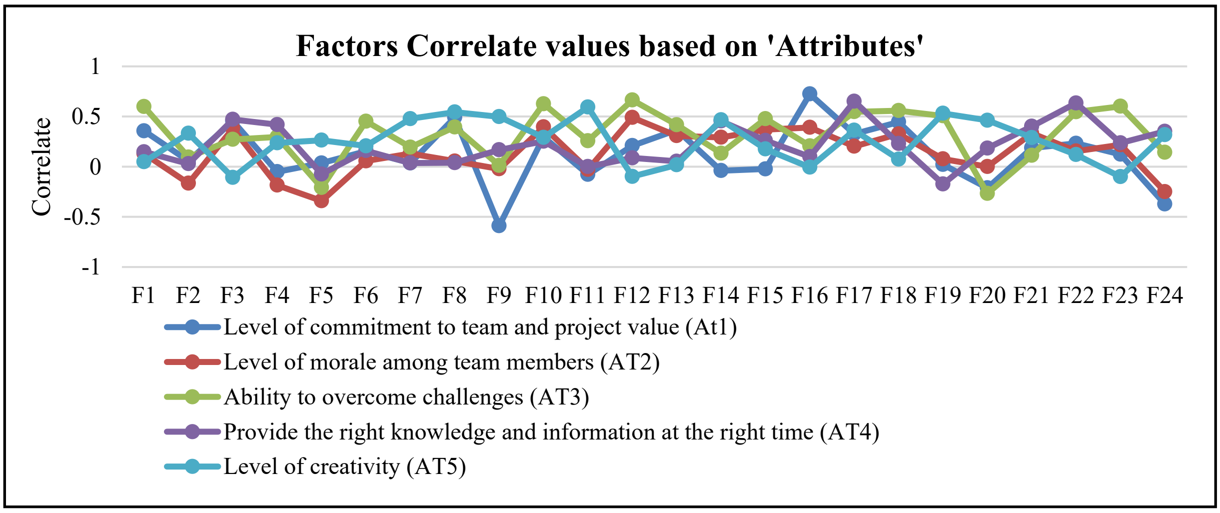

Figure 6: Factors Correlate Values Based on Attributes for Survey Result

Figure 6 presents the results of Pearson's test, which shows the correlations between factors and attributes based on their mean prevalence values. This helps to identify the factors that have a negative impact on team alignment. Positive factors are those that can enhance an attribute by improving the related factors. If the negative factors are improved, there can be a considerable change in the attribute. For example, in attribute four, which is the most critical attribute, the influential factors are F19 and F5. In attribute two, the most influential factors are F5 and F24. In other words, improving these four factors will significantly affect the level of team alignment.

This research presents a method for assessing team performance and maintaining team alignment throughout construction projects, based on the team, project, and corporate values. The framework allows for monitoring team members' progress and performance in relation to these values, identifying influential factors and aligned team traits for each project depending on its value. This will help team leaders identify strengths and weaknesses and set monthly and yearly objectives to improve output. The framework is evaluated through a case study of an IPD project at a construction business.

To create a quantitative approach for a qualitative characteristic, the developed instrument and methodology may benefit both academics and industry, especially in assessing team performance using the TVD. The main contributions of this study are:

Emphasizing the importance of team alignment for the successful use of TVD and establishing a correlation between factors, attributes, and the degree of team alignment.

Providing a system for assessing team performance, establishing a framework for evaluating multiple correlation types, and creating a connection map to assess the degree of team alignment.

The results of Pearson's test show that the degree of correlation between factors and attributes is important to the value of team alignment, and the connection is dynamic, and changes based on the expert panel's rating.

Outlining how a team alignment tool can be used to assess a team's performance in the AEC industry or any other team-based context, such as in the medical and commercial industries.

Addressing team alignment issues in construction projects can result in project failure due to collaboration restrictions and impediments at every stage of the building process.

CONCLUSION

This paper aims to address the challenges of team alignment in construction projects, which are often plagued by teamwork constraints and barriers that can lead to project failures. By drawing lessons from these constraints, team leaders can establish appropriate factors and attributes to monitor and evaluate team performance using the proposed methodology and framework. The case study presented in this paper demonstrates how project leaders can identify and improve team weaknesses and leverage team strengths to improve project productivity. In team-based industries, the team alignment framework can be used to evaluate team performance, outcomes, and risks, as well as to identify process improvements. To enhance the efficiency of this framework, future research should explore ways to automate it and develop a simulation tool.

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BUILDING A LEAN HOUSE WITH THE THEORY OF CONSTRAINTS FOR CONSTRUCTION OPERATIONS IN ZIMBABWE: A CONCEPTUAL FRAMEWORK

Cynthia Moyo[1] and Fidelis Emuze[2]

ABSTRACT

The poor performance of construction projects in Zimbabwe, evidenced by cost overruns, extensive delays, reworks, defects, and accidents, has resulted in the need for cost-effective strategies such as the theory of constraints and lean construction (LC). This is because Lean drives out waste, and the theory of constraints (TOC) identifies constraints on which to act to improve performance. By focusing Lean initiatives on construction projects, TOC will lead to better improvements in performance. Although similar studies have been undertaken in other countries, they need to be more contextually relevant due to the myriad of economic challenges synonymous with the Zimbabwean construction industry. A critical review of relevant literature was conducted to observe how TOC allows for identifying constraints hindering progress on construction projects while LC tools would provide solutions. In effect, LC and TOC could reverse poor outcomes of construction operations in Zimbabwe. This conceptual paper thus proposes a framework that identifies constraints using TOC, followed by an evaluation of Lean tools suitable to deal with the identified constraints. The foundation of the lean house will engender effective problem-solving to remove bottlenecks in the design and construction processes.

KEYWORDS

Construction operations, Lean, theory of constraints, performance, Zimbabwe

INTRODUCTION

Construction projects involve various actors whose activities greatly influence project success, such as the client or project owner, the consultant (architects, engineers, and quantity surveyors), and the contractors (Jin et al., 2017). Even though these parties have one goal: to make a profit, the multi-party working situation involved in construction projects results in conflicts and disputes, which bring direct and indirect cost consequences to clients and contractors (Yates and Hardcastle 2002). According to Goldratt (1991), every company's goal is to make money at present and in the future. The term constraint is defined as any element hindering the company's achievement of that goal. Theory of Constraints (TOC) is an approach that identifies the constraint and offers a solution for its mitigation (Pacheco et al., 2019). The TOC recognizes that constraints on any system restrict maximum performance concerning the goal (Siha, 1999).

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In the construction industry, that goal is to profit through increased productivity and minimized waste.

Waste minimization can also be achieved through lean construction (LC). LC involves converting waste into value by reducing waste, improving communication, and promoting teamwork integration through common tools and techniques (Emuze et al., 2014; Srinivas, 2020). Furthermore, LC creates a culture where the occurrence of problems is minimal due to benefits such as a reduction of waste, a decrease in inventory, advanced quality, better system flexibility, reduced variability, and amplified problem visibility (Abdullah et al., 2009). In addition, it ensures conventional flow and an improved capability to deal with uncertainty and difficulty in construction project delivery (Ruin et al., 2016). Maske and Valunjkar (2020) postulated that the LC method had been extensively articulated in developed countries; however, it has yet to attain limited and contextual applications. Lean production is a technique that Toyota Motor Company first implemented in the 1950s (Aziz and Hafez, 2013). Lean Thinking was first introduced in construction by Koskela to tackle certain features of building projects (Salvatierra-Garrido et al., 2010). Koskela et al. (2002: 212) define LC as "a way to design production systems to minimize waste of materials, time and effort to generate the maximum possible value". Koskela (1992) highlights that construction could significantly improve by identifying and eliminating non-value-adding activities.

The profitability of most construction projects depends on construction productivity; if this is not fully addressed, projects will incur cost and time overruns (Besklubova and Zhang, 2019). According to Aziz and Hafez (2013), construction productivity has declined worldwide over the past 40 years, hence the need to implement approaches such as TOC and LC to improve performance. In Zimbabwe, cost, time and quality concerns remain prevalent in infrastructural construction projects (Moyo et al., 2019; Bhebhe, 2022). To add to this, Chazireni and Chagonda (2018) highlight health and safety inadequacies that also affect the performance of construction projects. Hence, cost, time, quality, and safety constraints hamper the success of construction operations in Zimbabwe. By combining LC and TOC, performance improvement can be achieved as waste will be eliminated from construction operations.

Although studies have been conducted on LC and TOC by Ju et al. (2000) in Singapore, Cameiro et al. (2009) and Santos et al. (2012) in Brazil, the implications of those results do not necessarily apply to Zimbabwe. This is because the construction industry in Zimbabwe is resource-restrained due to the foreign currency shortages, prolonged power outages, and ever-increasing inflation estimated at more than 400% experienced over the past five years (Kuwaza, 2019). Therefore, it is essential to identify cost-effective performance improvement strategies applicable to the unique situation currently experienced in Zimbabwe. Hence this paper is the first step of a doctoral study that aims to develop guidelines for using the theory of constraints (TOC) and lean to improve construction operations in Zimbabwe.

THE STATEMENT OF THE PROBLEM

Challenges of time and cost overruns, quality issues, health and safety inadequacies, productivity, performance, and sustainability have been dominant in the construction industry in Zimbabwe (Chazireni and Chagonda, 2018; Mhlanga, 2019; Moyo and Chigara, 2021). Oke et al. (2019) also explained that waste, such as materials, resources, time, movement, production, and creativity, affect the construction industry's performance. Therefore, waste-laden construction operations in the Zimbabwean construction industry promote performance concerns related to cost, time, quality, and safety. Implementing lean tools, coupled with the fact that contractors do not know how to identify, understand, and remove constraints in construction operations, is yet to be operationalized as a resolution in the study area.

Therefore, this study seeks to provide a framework for TOC and LC to improve construction operations in Zimbabwe. The overall benefit is the achievement of key targets within the sustainable development goal of ensuring sustainable production and consumption patterns from the construction industry perspective (United Nations Department of Global Communications, 2020).

Primary research question and secondary research questions

The primary research question elicits responses to what can be done using the theory of constraints (TOC) and Lean to improve construction operations in Zimbabwe. The secondary research questions require responses on the following: what needs to change in construction operations, what can be done for construction operations to change, what can project actors do to cause the change in construction operations, what lean tools will improve construction operations, and what can be done through combining lean and TOC to improve construction operations in Zimbabwe based on literature.

These questions will be answered by first interrogating the causes of cost, time, quality, and safety challenges, thereby indicating what needs to change in construction operations in Zimbabwe. The mitigating strategies for these challenges are identified, highlighting how construction operations can change. Next, implementing the principles of the Toyota Production System (TPS) and Fukuda Production System (FPS) will be examined to show how they can cause the change required in construction operations. Also, lean tools that can improve construction operations regarding cost, time, quality, and safety performance will be assessed. Lastly, recommendations on what construction operation improvements can be achieved through combining the TOC and Lean.

PERFORMANCE OF CONSTRUCTION PROJECTS

The performance of construction projects has been topical over the past two decades, as alluded to by various authors hereafter.

COST PERFORMANCE OF CONSTRUCTION PROJECTS

Moyo et al. (2019) highlight the prevalence of cost overruns in construction projects and suggest the need for sufficient awareness and regulation on decent work conditions for construction workers as it has a bearing on their productivity. Nyoni (2019) indicates how rare it is in Zimbabwe for construction projects to be completed within the estimated budget, thus the importance of finding solutions to these cost performance challenges. According to Moyo and Chigara (2022), the performance of infrastructural projects has been challenging, thus leading to the interrogation of the causes of cost overruns in Zimbabwe. It is essential to identify the causes of cost overruns to cause the change required in the performance of construction projects in Zimbabwe.

TIME PERFORMANCE OF CONSTRUCTION PROJECTS

According to Nyoni and Bonga (2017a), the issue of delays is one of the severest performance challenges in construction projects, and their effect has a bearing on the overall economy of such developing nations. Nyoni (2018) also expresses concern over prevalent delays in most construction projects in Zimbabwe; he explains how these delays culminate in cost overruns and quality defects. Ngendakumana and Kakono (2020) studied the causes of construction project delays in Zimbabwe's public service and identified lack of adequate funds, project variations and inadequacy of resources as the major causes. Nyoni and Bonga (2017b), in their study of critical success factors in the construction sector, highlight the challenge of incomplete projects and postulate critical success factors to significantly improve project effectiveness and efficiency hence providing solutions to time performance and cost performance challenges.

QUALITY PERFORMANCE OF PROJECTS

In Zimbabwe, there has been great concern over poor workmanship on certain high-impact infrastructural projects countrywide (Bhebhe, 2022). This is evidenced by the recently opened registry building in Harare, which is already developing cracks, water leakages, and non-functioning elevators (Chibamu, 2022). This brings out the need for these performance improvement strategies, hence the importance of this study.

SAFETY PERFORMANCE OF CONSTRUCTION PROJECTS

Chigara and Moyo (2014), postulate that there is a high injury frequency rate in the construction sector of Zimbabwe which is estimated at around 2.34%, therefore higher than the ILO-prescribed rate of less than 1%. Further, Chigara and Smallwood (2017) state that the Zimbabwean construction industry is still experiencing injuries at an increasing rate. Charizeni and Chigonda (2018) concur that safety challenges are prevalent on construction sites, hence the importance of continuous performance improvement.

This shows that cost, time, quality, and safety constraints hamper the success of construction operations in Zimbabwe. Additionally, diverse challenges affecting the construction industry's performance in Zimbabwe led Moyo and Chigara (2021a) to interrogate the barriers to implementing LC. These barriers included management-related, design management-related, technical issues, change management-related, quality management-related, and human capital management-related. These findings were supported by other researchers in developing countries (Khaba & Bhar, 2017; Sarhan, et al., 2018; Albalkhy & Sweis, 2020), as they also identified similar barriers. By combining LC and TOC, performance improvement will be achieved as waste will be eliminated in the parts of the system that are the most significant constraints.

THEORETICAL FOUNDATION

The study's theoretical foundation consists of the theory of constraints and lean theory, which are supported henceforth.

THEORY OF CONSTRAINTS (TOC)

The TOC is a theory developed by Dr. Eliyahu Goldratt in 1984 (Goldratt and Cox, 2004). This theory suggests that every organization's goal is to make a profit. However, organizations' constraints hinder the achievement of this goal to make a profit. TOC identifies critical constraints and suggests improvement of activities that would elevate the constraints and inherently prioritize them (Upreti et al., 2020). Hence, TOC is a continuous improvement process because no matter how successful an organization is in achieving its goals, constraints will always exist; hence, TOC focuses on identifying and managing these constraints within organizations (Pegels and Watrous, 2005). Goldratt (1991) identified five steps of the focus process of managing these constraints within organizations, including identifying the constraints, deciding how to exploit the needs of the constraint, subordinating and synchronizing the constraints, elevating the constraints, and, lastly, repeating the process. These steps form the foundation of this study. Therefore, TOC is expected to play a significant part in improving performance.

LEAN APPROACH FOR CONSTRUCTION

Lean principles aim at eliminating or reducing non-value-adding activities (e.g. waste, variation, waiting, low standard) and promoting value-adding activities (e.g. ensuring quality and safety, sustainability, environmentally friendly, customer satisfaction) (Ahmed et al., 2021). Although each organization must develop its way of doing business, The Toyota Production System (TPS) has achieved success for Toyota in terms of waste minimization and value addition. This success makes it a solid foundation for implementing lean principles. The TPS's 14 principles are critical for achieving and responding to constraints as they are supported by pillars of continuous improvement and respect for people (Liker, 2004). In Japan, the TPS was adapted for construction projects by the FPS to improve the efficiency of construction work and lower construction costs (Nakagawa and Shimizi 2004). The FPS flow was suggested as follows:

1. Setting the goal
2. Establishment of indices to achieve the goal (this involves the establishment of Just In Time, and Standard Operating Procedure Documents (SOPD)
3. Setting of target figures for the indices (this includes continuous revisions to the SOPD and target figures)
4. Implementation to attain the goal (this involves checks and confirmations on whether the goal is being achieved.
5. Checking and confirming that target figures have been achieved (If the goal is not achieved, then the cause is examined, and if the goal is achieved, then the procedural steps are standardized
6. Continuous Improvement

The FPS is a more feasible foundation for implementing LC guidelines in the Zimbabwean construction industry. The FPS has the potential to respond to the constraints in the 'setting of the goals' stage and accommodates LC tools within its flow. Above all, it caters to continuous improvement, allowing for the constant generation of constraints and appropriate responses.

METHODOLOGY

The conceptual paper is based on the critical literature review of the theory of constraints and LC theory. The conceptual framework developed is the preliminary stage of a doctoral study expected to solve the challenges of performance experienced in construction operations in Zimbabwe. The study is based on the review of literature on TOC, LC tools, and performance challenges in the Zimbabwean construction industry. The keywords for the search included "Theory of constraints", "Lean construction with the theory of constraints", "lean tools", lean construction", lean construction tools", "lean house", and "Zimbabwean construction constraints". The search was dominated by, but not limited to, Emerald, Science Direct, relevant textbooks on TOC, and publications in the International Group of Lean Construction (IGLC) repository. Articles relating to developing countries were preferred as the study context aligned more with them. An attempt was made to consider the latest articles where it was possible. Content analysis was employed to extract relevant information for developing the conceptual framework, as shown in Figure 1.

CONCEPTUAL FRAMEWORK

Figure 1 shows the proposed framework for providing TOC and Lean guidelines for improving construction operations. The foundation of the lean house is built on ensuring standardization and stability in responding to constraints within construction operations. Achieving this culminates in guidelines that can be utilized for construction operations. The TOC is also foundational as a continuous process for identifying new constraints as and when they become significant. The identification of constraints using the TOC requires two main pillars. The first pillar is the Lean tools that can be implemented to resolve and continuously improve the constraints.

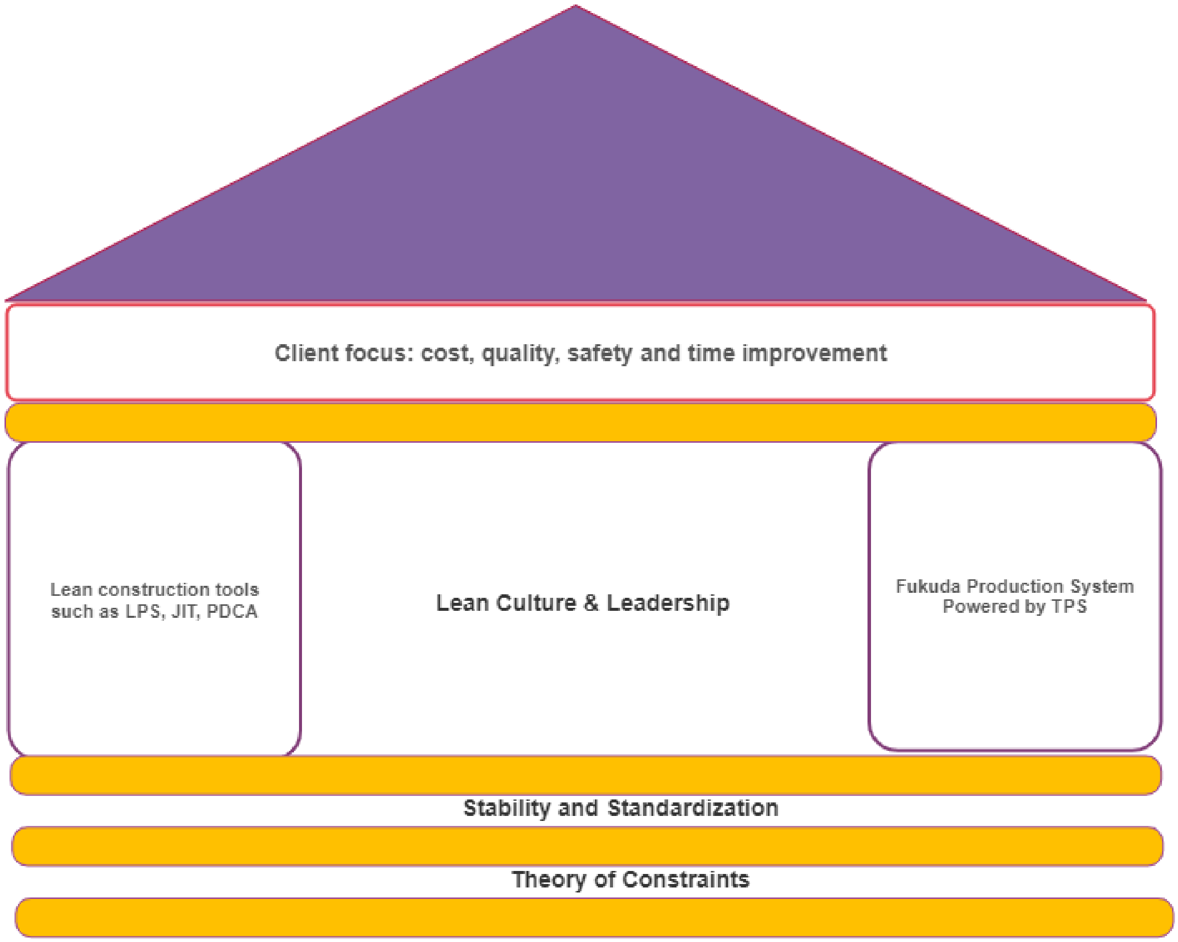

Figure 1: Conceptual Framework- Lean house with the theory of constraints

The lean tools are expected to be implemented in accordance with the TOC steps of identification, exploit, subordinate, elevate and repeat. These lean tools include the Last Planner System, Total Quality Management, Just-in-time and PDCA. The selection of lean tools should be based on context, usability in developing countries and the ability of the tools to contribute to the continuous improvement of construction operations. The other pillar encourages the adoption of the TPS principles as adopted within the construction industry as the FPS. The requirements of the two pillars can only be achieved through adopting lean leadership and organizational culture. All project actors must inculcate lean leadership and organizational culture for the guidelines to be successful. Using lean tools, the FPS principles must lead to cost, time, quality and safety improvements in construction operations. This is envisaged to be a continuous improvement process. The constituents of the proposed framework are briefly reviewed henceforth.

CONSTRUCTION OPERATIONS CONSTRAINTS

To improve construction operations in Zimbabwe, several changes are required in the aspects of cost, time, quality, and safety. Cost aspects require changes in respect of low productivity of the workforce, idle plant and machinery, material wastage on construction sites as well as plant and machinery inefficiency as these have caused poor performance of construction operations. Moreso, changes in time aspects are necessary, including low productivity of the workforce resulting in delays, ineffective coordination, and poor communication among stakeholders. There are also quality changes required to improve the quality performance of operations, and these are the occurrence of defects, reworks, use of poor quality materials, and poor workmanship. Finally, the safety aspects that require change are the number of accidents on construction sites, the frequency of absenteeism of workers from sites, high employee turnover, and low workforce morale.

The abovementioned changes are required to create simple and practical solutions to construction operations' cost, time, quality, and safety challenges. Therefore, effecting the changes suggested will result in increased productivity, less waste paying for idle plant and machinery, efficient use of materials and efficiency of plant and machinery hence improving cost performance of construction operations. Achieving the changes required for time aspects will result in enhanced productivity of the workforce, effective coordination of work, and effective communication amongst stakeholders, thus solving the challenge of delays. Moreso, changes in quality challenges will result in the minimization of reworks, reduced defects, improved quality of end products, and achievement of client satisfaction. Lastly, safety changes will lead to reduced accidents and incidents, reduced absenteeism, and employee turnover, thus increasing productivity and improvement in the morale of workers.

To build a secure and stable improvement environment for the changes required, the research proposes using the FPS, which was developed specifically for construction projects from the TPS. The FPS has principles that allow for performance improvement of construction operations by setting goals for the whole organization, individuals, and construction projects. The principles enable setting safety and quality standards on construction projects required for individuals, construction projects and the organization. Furthermore, these principles provide an improved environment for cost and time challenges. It allows for the identification and continuous reduction of waste, which is the main cause of cost and time overruns. Moreover, the principles allow for continuous improvement through its people-centred approach, realizing that performance can only be achieved if employees are trained, offered incentives for waste reduction, and involved at every stage.

LEAN CONSTRUCTION TOOLS

A plethora of Lean tools exists in the manufacturing and construction sectors. However, the nature of the manufacturing and construction industries varies with the relevant Lean tools (Moghadam and Al-Hussein, 2014). Therefore, selected lean tools relevant to the construction industry are reviewed in Table 1.

Also, the major findings and the constraints addressed in those studies are presented and analyzed for inclusion in the study's conceptual framework. It is practically impossible to operationalize all the suggested LC tools in this study. From the findings in Table 1, the LC tools most effectively responding to cost, time, quality, and safety include the Last Planner System (LPS) and Total Quality Management (TQM). LPS has been the most common LC tool utilized by many researchers, while TQM had a significantly high impact on individual performance, as reported by Li et al. (2019). In addition, the FPS suggests using the Just-in-time (JIT) and Plan, Do, Check and Act cycle (PDCA) on construction sites (Nakagawa and Shimizu, 2004). Therefore, this study has incorporated the LPS, TQM, JIT and PDCA tools for contextualization and standardization within the Zimbabwean construction industry to resolve the constraints of cost, time, quality, and safety. The LPS shapes workflow and responds to project variability in construction (Ballard, 2000). TQM ensures quality management of every stage of construction operations and continually invests in improvement opportunities (Radnor, 2000). The JIT tool reduces waste by ensuring the delivery of materials when required, while the PDCA periodically emphasizes safety, schedule, and quality improvements (Nakagawa and Shimizi, 2004).

Table 1: Lean construction tools from previous studies

Lean construction tools	Findings	Source	Constraints targeted
Last planner system	The proposed Last planner system could significantly improve productivity in developing countries.	Ahiakwo et al (2012)	Cost and Time
Last planner system, Increased visualization, The Five S's Process, Fail Safe for Quality and safety, First, run studies.	Although respondents agreed on their importance, their implementation could be improved by a lack of awareness.	Enshassi and Abu Zaiter (2014)	Safety
Last planner system	Success was achieved on sites where total management commitment was made towards lean tool implementation.	Raghavan et al (2014)	Time
5S, Quality control and Last planner system	The last planner system enabled the monitoring of improvement actions	Berrior et al. (2015)	Cost, Time and Quality
Last planner system	Existing gaps in planning and scheduling vs last planner systems	Dave et al. (2015)	Time
Planning and controlling the production, Kanban, Autonomation, Flows, Production, Transparency, Cleanness, organization and safety.	Lean audit checklist for the various sites' implementation of a standardized manual on lean tools revealed a positive contribution to project performance goals.	Fernandes et al (2016)	Cost, Time, Quality and Safety
Last planner system	The lean tool successfully contributed to the successful completion of four case study projects concerning cost, time and safety.	Karanjawala and Baretto (2018)	Cost, Time, Safety
Last planner system	Work involvement by the last planner improved the performance of the project.	Sundararajan and Madhavi (2018)	Time
Last planner system, a Visualization tool, Six step plan (6S), Just-in-time (JIT), Total quality management (TQM)	TQM had the highest impact on individual performance, while the Last planner system had the least.	Li et al. (2019)	Cost, Time, Quality and Safety
Last planner system	Implementation of the tool led to a positive impact during the COVID- 19 pandemic	Veran-Leigh and Brioso (2019)	Cost, Time, Quality and Safety

PERFORMANCE IMPROVEMENT

The competition in the construction industry has become intense, as evidenced by the large numbers of contractor companies in various countries, which has pressured contractors to minimize costs as much as possible (Bayram, 2017). For the success of construction projects, the ability to deliver a quality product safely is vital (Loushine et al., 2006). According to Buniya et al. (2021), poor safety performance has been a severe challenge in the construction industry. Construction projects are increasingly becoming more complex, competitive and collaborative. Hence timely delivery is critical nowadays (Kerzner, 2022). Delays in construction projects often affect the overall performance of projects in areas such as profitability, efficiency and safety (Gunduz and Al-Naimi, 2022). By addressing the root causes of cost and time overruns and quality and safety challenges, performance will be improved, leading to the success of construction projects.

CONCLUSION

The performance of construction projects in Zimbabwe has been an issue, with most of them failing due to cost overruns, time overruns, quality concerns and safety challenges. This was conceptualized to solve the mentioned problems, which perpetrate waste (non-value adding activities) in Zimbabwe through LC. By applying TOC to construction projects, contractors can identify, understand, and remove constraints in operations to aid work progress. Therefore, this study presents the preliminary step of a doctoral study, which should culminate in guidelines that inform how TOC and LC will become change agents in construction in Zimbabwe. The research will further elicit responses from industry participants to answer the research questions and draw up recommendations for the main study.

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PERCEPTION OF PROJECT MANAGEMENT AMONG CONSTRUCTION WORKERS: A SURVEY IN DENMARK

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ABSTRACT

According to the Lean philosophy, continuous improvement relies on an investment in people, and Lean methods and tools cannot be sustained without labor. Hence, knowledge about workers' job satisfaction is highly valuable for improving the efficiency of the construction industry. For that reason, a survey was created and applied to understand the level of job satisfaction among construction workers in Denmark within three areas: (1) Project Management; (2) Work Environment; and (3) Health and Safety. The descriptive survey method was adopted as the primary research approach. The study comprised five steps: (1) link to the theoretical level; (2) survey design; (3) pilot test; (4) data collection; and (5) data analysis. This paper presents a part of the survey results concerning project management. The results reveal the most significant issues to be unrealistic commitment plans and poor communication with management and other stakeholders. Respondents generally feel encouraged to suggest improvements to the current practice, however, their knowledge about Lean concepts is very limited. The paper presents two contributions: (1) the identification of the perception of project management among construction workers in Denmark and (2) a survey template that can be applied by others to understand construction workers' job satisfaction levels.

KEYWORDS

Job satisfaction, survey, lean construction, collaboration, culture of respect.

INTRODUCTION

At the core of the lean philosophy lies the concept of increasing production efficiency by continuously eliminating waste, together with the equally important concept of "respect for people" (sometimes called "respect for humanity") (Howell et al., 2017; Liker & Meier, 2006; Ohno, 1988). According to the lean philosophy, continuous improvement relies on an investment in people, not equipment or systems (Hakes, 1991), and lean methods and tools cannot be sustained without labor (Emiliani, 2005). In other words, the "respect for people" principle enables continuous improvement (Emiliani, 2006). This concept does not mean creating a stress-free environment with lots of amenities for employees, rather it implies creating challenging environments in which people can learn and grow and are encouraged to raise problems to the surface (Liker & Meier, 2006). Employees are entrusted with more responsibility and authority, which makes them feel empowered (Marksberry, 2011).

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According to Howell et al. (2017), behaving in accordance with the "respect for people" principle promotes psychological safety. Psychological safety is a crucial motivating factor for engaging in learning behaviors in project teams, which leads to improved team performance (Bossche et al., 2006). Thus, implementing "respect for people" in the organizational culture can positively impact team effectiveness. The principle is also strongly correlated with job satisfaction (McKinnon et al., 2003).

Despite the emphasis in lean philosophy on the importance of respect for people, the principle is often misunderstood or left out in the implementation process (Coetzee et al., 2019; Emiliani, 2006). Considering the aforementioned dependencies, this could affect project performance and job satisfaction.

In a construction context, job satisfaction has also been identified as one of the most influential motivators for improved labor productivity (Kazaz & Ulubeyli, 2007). Hence, knowledge about workers' job satisfaction is highly valuable.

In 2016, the Danish trade union 3F conducted a survey among construction workers in Denmark to disclose the issues that the workers found to be most dissatisfying about their jobs (Dalsgaard et al., 2016). The answers showed that the most significant issues were: (1) many heavy lifts on site (reported by 59% of respondents) and (2) too much wasted time due to poor planning of the project (reported by 55%) (Dalsgaard et al., 2016).

Since the 3F national survey in 2016, no other studies have been conducted on a national scale concerning job satisfaction in the Danish construction industry. Moreover, to the authors' knowledge, no study has been made regarding the general perception of project management, health and safety, and the overall work environment among construction workers in Denmark. The present paper, therefore, presents a comprehensive survey designed to investigate these three themes.

The survey results are too comprehensive to present in full in this paper. Thus, the goal of this paper is understanding the level of knowledge and the subjective perception among construction workers on Danish construction sites of only one of the three themes, namely project management, including knowledge about Lean concepts. Moreover, this paper presents the contribution of a tool in the form of a survey template (available upon request) that other researchers and practitioners can apply to gain knowledge about job satisfaction in other countries. Of course, minor adjustments should be made to ensure relevance in the context where it is applied, e.g., regarding economy and ethnicities. Applying the same survey in other countries would make it possible to compare results and raise the general knowledge level in this important area.

LITERATURE REVIEW

Questionnaires have been widely applied in research to investigate various topics that affect job satisfaction and the mental and physical well-being of employees. Though the phrasing of topics and questions differ among studies, the overall themes are, in many cases, comparable. Table 1 summarizes the main themes treated in the identified previous literature on surveys of workers, mainly within the construction industry, but also including healthcare and social services.

As shown in Table 1, nine themes have been identified among the studies, namely (1) Workers' contractual characteristics, (2) Rewards, (3) Health and safety, (4) Relations with management, (5) Relations with coworkers, (6) Communication, (7) Worker engagement, (8) Work environment and culture, and (9) Project management. Some studies have included many different themes (Ahmad et al., 2020; Kazaz & Ulubeyli, 2007; Spector, 1985) while others focus on few themes (Dainty, 2007; Han et al., 2019).

Table 1: Themes Evaluated in Worker Surveys

Reference	(1) Workers' contractual characteristics	(2) Rewards	(3) Health & Safety	(4) Relations with management	(5) Relations with co-workers	(6) Communication	(7) Worker engagement	(8) Work environment and culture	(9) Project management
Rani et al. (2022)	X		X	X		X		X	X
Ahmad et al. (2020)		X	X	X	X	X	X	X	
Asilian-Mahabadi et al. (2020)			X	X	X				X
Han et al. (2019)			X						
Gomez et al. (2019)			X	X	X	X		X	
Dalsgaard et al. (2016)			X			X	X	X	
Hosseini et al. (2014)		X	X	X	X		X	X	
Marzuki et al. (2012)	X	X		X	X			X	
Chileshe and Haupt (2010)		X	X	X	X		X	X	
Dainty (2007)						X		X	
Kazaz and Ulubeyli (2007)	X	X	X	X	X	X	X	X	
Che Hassan et al. (2007)			X	X	X	X	X		X
Spector (1985)	X	X		X	X	X		X	X

The first theme concerning workers' contractual characteristics is included in four of the identified studies under different topics, such as Salary package (Rani et al., 2022), Fulfilment of higher order needs (Marzuki et al., 2012), Timeliness of remuneration and Social insurance (Kazaz & Ulubeyli, 2007), and Satisfaction with pay (Spector, 1985). This theme is closely connected with theme 2, rewards, which was mentioned in six studies, whereof three were also mentioning theme 1. Besides the word Rewards (Marzuki et al., 2012), this theme has also been addressed with e.g., Recognition (Ahmad et al., 2020), Incentive payments (Kazaz & Ulubeyli, 2007), and Contingent rewards (appreciation and recognition) (Spector, 1985).

Health and safety, theme 3, is one of the most widely applied themes in the literature, included in ten of the 13 studies presented. The topics within the health and safety questions vary, some examples are Safety supervision and management (Asilian-Mahabadi et al., 2020), Psychological safety (Gomez et al., 2019), and Risk behavior (Che Hassan et al., 2007), besides the general Health and safety monitoring (Han et al., 2019; Kazaz & Ulubeyli, 2007; Rani et al., 2022).

Themes 4 and 5, relations with management and coworkers, respectively, are also closely connected. All studies that have included one have also included the other, except for Rani et al. (2022), where only the theme relations with management is included, referred to in multiple topics, e.g., Collaboration between top management and employees and Project leadership. Other studies phrase the relations with management theme in topics such as Leadership (Ahmad et al., 2020) and Supervision (Spector, 1985), to name a few. Topics regarding relations with coworkers (Chileshe & Haupt, 2010; Hosseini et al., 2014; Kazaz & Ulubeyli, 2007; Marzuki et al., 2012; Spector, 1985) are also called Teamwork (Ahmad et al., 2020) and Social activity opportunities (Kazaz & Ulubeyli, 2007). Theme 6, communication, is mostly referred to with the word communication, except in Kazaz and Ulubeyli (2007), where the topic is called Sharing problems and their results.

The topics that fall under theme 7, worker engagement, have more diverse wordings, such as Empowerment and participation (Ahmad et al., 2020) and Personal role (Che Hassan et al., 2007). Theme 8, work environment and culture, is represented through topics in ten of the 13 studies. Some examples of these topics are Migrant issues and Racism (Dainty, 2007), Caring about each other (Gomez et al., 2019), and Work discipline (Kazaz & Ulubeyli, 2007).

Theme 9, project management, is only being treated in a few studies. In the ones that include this theme, it is also being called Project progress (Rani et al., 2022), Contract management (Asilian-Mahabadi et al., 2020), and Operational procedures (Spector, 1985). Table 2 presents additional information on the 13 studies.

Table 2: Approaches Adopted in Worker Surveys

Reference	Industry	Area	Method	Resp.	Country
Rani et al. (2022)	**C**	**Wellbeing**	**I + Q**	**205**	**Malaysia**
Ahmad et al. (2020)	**H**	**Job satisfaction**	**Q**	**343**	**Malaysia**
Asilian-Mahabadi et al. (2020)	**C**	**Safety**	**I + Q**	**69+393**	**Iran, Oman, Syria**
Han et al. (2019)	**C**	**Safety**	**Q**	**155**	**China**
Gomez et al. (2019)	**C**	**Safety**	**Q**	**64**	**USA**
Dalsgaard et al. (2016)	**C**	**Job (dis)satisfaction**	**Q**	**2.597**	**Denmark**
Hosseini et al. (2014)	**C**	**Job satisfaction**	**Q**	**72**	**Australia**
Marzuki et al. (2012)	**C**	**Job satisfaction**	**Q**	**56**	**Indonesia**
Chileshe and Haupt (2010)	**C**	**Job satisfaction**	**Q**	**65**	**South Africa**
Dainty (2007)	**C**	**Health, safety**	**I + Q**	**68+17**	**England**
Kazaz and Ulubeyli (2007)	**C**	**Productivity**	**Q**	**82**	**Turkey**
Che Hassan et al. (2007)	**C**	**Health, safety, environment**	**C + Q**	**100**	**Malaysia**
Spector (1985)	**H & SS**	**Job satisfaction**	**Q**	**3.148**	**USA**

C=Construction; H=Healthcare; SS=Social Services; Q=Questionnaire; I=Interview; C=Checklist

It can be seen from Table 2 that the application of the questionnaires and interviews has been limited to a single country in all of the studies except Asilian-Mahabadi et al. (2020), which included both Iran, Oman, and Syria in their study. Moreover, only half of the surveys have more than 100 respondents. Consequently, the results cannot be used to draw valid conclusions in a broader perspective, such as nationwide or industry wide. Furthermore, some papers (Che Hassan et al., 2007; Dainty, 2007; Kazaz & Ulubeyli, 2007; Marzuki et al., 2012) do not include the applied questionnaire or another representation of the questions asked, which hinders further data collection.

Among the 13 studies, there is only one example of the same questionnaire being applied in a different setting to compare the results, namely the study by Hosseini et al. (2014) which reuses the survey developed by Chileshe and Haupt (2010). Even though there are many similarities between the studies, the different formulations and definitions of topics makes it difficult to directly compare the results, not least because different scales and indexes have been used to evaluate the survey responses. An alignment of surveys across countries would expand the possible learnings and uses of the results.

As mentioned above, only four of the 13 studies include the project management theme explicitly. However, almost all the other themes can be said to arise from project management, be it communication, relations, or contractual characteristics, as these are all results of decisions made within the project management team. Project management is a key element when it comes to understanding job satisfaction and is, therefore, chosen as the focus area for this paper.

RESEARCH METHODOLOGY

The study adopted the survey method as the main research approach. The present survey can be classified as descriptive (Babbie, 1990). Descriptive survey research aims to understand the relevance of a specific phenomenon and describe the distribution of the phenomenon in a population (Forza, 2002). The phenomenon of the present study consists of the job satisfaction of construction workers, and the survey population is construction workers on Danish job sites. The present survey comprised the following five steps (Figure 1): (1) link to the theoretical level; (2) survey design; (3) pilot test; (4) data collection; and (5) data analysis.

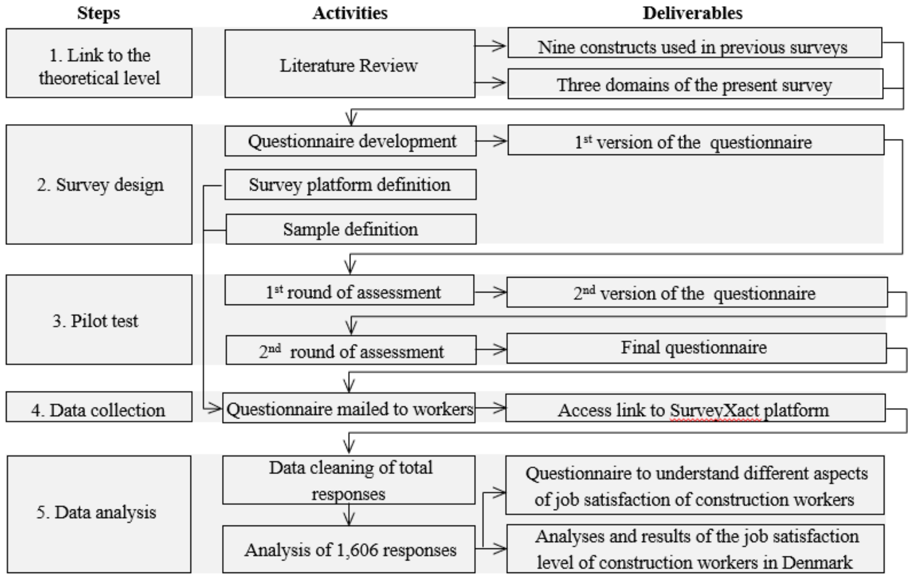

Figure 1: Research Methodology

STEP 1: LINK TO THE THEORETICAL LEVEL

In this step, the authors conducted a literature review to find questions and the constructs (i.e., theoretical concepts) that have already been used in similar studies. As presented in the Literature review section, the authors identified nine constructs generally used in job satisfaction surveys. Lastly, in this step, the authors selected the three main domains that the present survey focuses on: (1) Project Management (PM); (2) Work environment (WE); and (3) Health and Safety (HS).

STEP 2: SURVEY DESIGN

Survey design includes all of the activities that precede data collection. This includes developing the questionnaire and defining the sample. Firstly, the authors identified a comprehensive number of questions and statements from previous studies through the literature review. Then, the questions identified were grouped into the three domains (PM, WE, and HS). Moreover, the authors conducted a reduction of the questions considering their relevance to the construction sector and questions that were too similar.

Secondly, the study population was limited to all construction workers of Danish job sites who are members of a union, including foreign workers. The union membership prerequisite was chosen because it is very common to be part of a union in Denmark, and thus cooperating with the unions for the distribution of the survey provided an opportunity for a large number of potential respondents. Moreover, the survey used non-probabilistic sampling to obtain as much data as possible.

The first version of the questionnaire comprised 48 questions grouped into four sections of 12 questions: (1) demographics (Section 1, S1 for short); (2) project management (S2); (3) work environment (S3); (4) health and safety (S4).

STEP 3: PILOT TEST

The questionnaire was evaluated in two rounds of assessment. The first evaluation consisted of a two-hour online meeting. During this meeting, the group of researchers evaluated the questionnaire together with two industry experts from a professional cooperation organization for Danish unions in the construction industry, called BAT (Danish: *Bygge- Anlægs- og Trækartellet*). Following the experts' suggestions, some questions were added (e.g., S1.10 - Kind of contractual involvement of your company in the current project) and others were removed (e.g., I am satisfied with my involvement in decisions that affect my work).

Then, the questionnaire was reviewed and sent to the experts by e-mail for a second round of evaluation. Moreover, during this round, the access link to the survey platform was sent to the experts to test the viability of the administration of the survey. After making some minor modifications, the questionnaire was finalized. The final questionnaire comprised 39 questions distributed as follows: S1 included 12 questions; S2 included 12 questions; S3 included 8 questions; and S4 included 7 questions.

The questionnaire was initially developed in English and then translated into four other predominant languages spoken on Danish job sites, those being: Danish, Polish, Romanian, and Italian.

STEP 4: DATA COLLECTION

The questionnaire was distributed as a hyperlink included in an e-mail to the respondents. The hyperlink led to SurveyXact; the institutional survey platform used by the university of the researchers. The survey was open for answers from January 4th to 20th, 2023. To increase the probability of success of the data collection, the researchers included the opportunity for respondents to win a reward. This consisted of a draw among all the respondents of 10 giftcards.

STEP 5: DATA ANALYSIS

A total of 2,406 survey responses were collected. To ensure consistency through the presentation of the results, the responses where not all the 39 questions were answered were excluded, which left 1,606 responses for analyzing. The data analysis was conducted with Microsoft Excel. Due to space constraints, the data analyses presented in this paper are mainly descriptive. However, the questionnaire results can also be used for conducting diagnostic and prescriptive analysis.

The demographic profile of the respondents is shown in Figure 2 and Table 3. Most respondents are males (91%) and Danish (95%). About one third (32%) are carpenters, and 58% of the respondents work as skilled workers. The distribution of age and experience is well balanced and similar to the known characteristics of the construction industry.

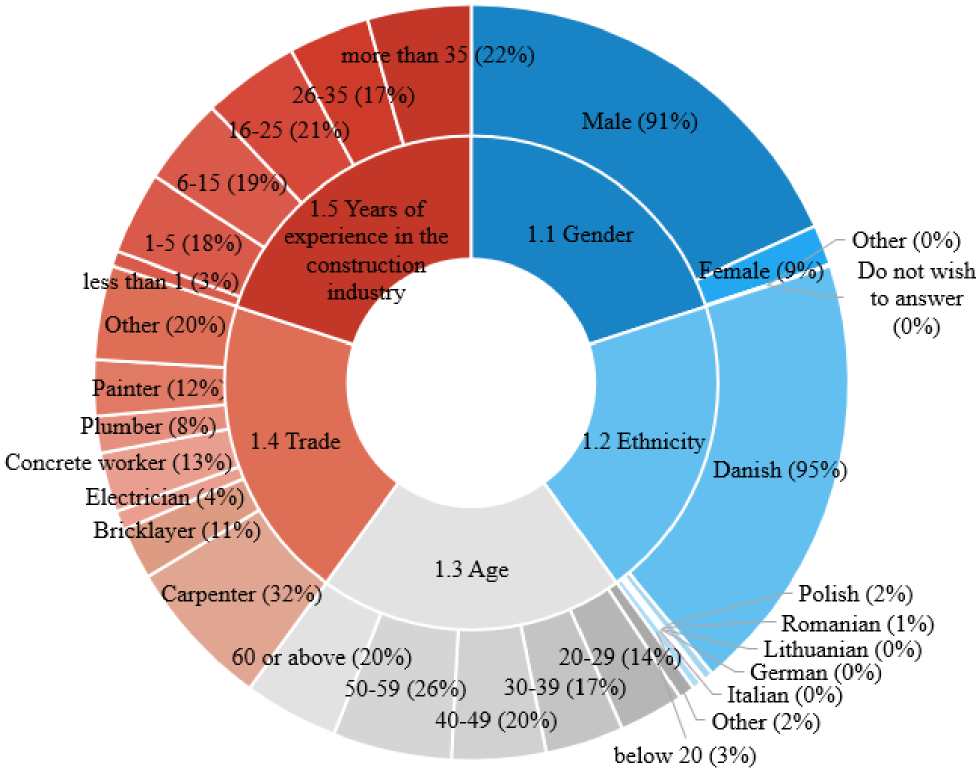

Figure 2: Demographic Profile of Respondents, Part 1

Table 3: Demographic Profile of Respondents, Part 2

Questions S1.6-S1.8		Frequency	Questions S1.9-S1.12		Frequency
6. Your position in the company you currently work in	Unskilled	15%	**9.Origin of the company you currently work in**	Danish	97%
	Apprentice	11%		Foreign	2%
	Skilled worker	58%		I don't know	1%
	Foreman	8%	**10.Kind of contractual in-volvement of your company in the current project**	Contractor	44%
	Other	8%		Subcontractor	34%
7.Years of experience you have in your current company	Less than 1	19%		Temp agency	1%
	1-5	40%		Other	10%
	6-10	15%		I don't know	11%
	11-15	8%	**11.Size of the current project**	Less than 1 mio DKK	23%
	More than 15	18%		1-10 mio DKK	24%
8.No. of employees in the company you currently work in	1	1%		11-100 mio DKK	14%
	2-9	18%		101-500 mio DKK	5%
	10-49	34%		More than 500 mio DKK	4%
	50-99	13%		I don't know	30%
	100-249	13%	**12.The kind of project you are currently working**	Civil works	15%
	250 or more	17%		New buildings	36%
	I don't know	4%		Building renovation	49%

RESULTS AND DISCUSSION

At the beginning of the Project Management section, the respondents were given a list of factors, which they were asked to rank using a 5-point Likert scale concerning the frequency of occurrence (Figure 3a). They were also asked to choose which two out of six communication issues that causes the most dissatisfaction for them (Figure 3b). Figure 3c shows the results of questions related to worker involvement.

The result of S2.1 (Figure 3a) shows that the factors that affect the flow of the project or cause delays the most according to the respondents are the commitment plan (M1 in Figure 3a) and space and communication issues (M6 and M10 in Figure 3a, respectively). The two factors with which workers are most dissatisfied are Factor 1 – Not getting enough information from their employers and Factor 6 – poor communication with other stakeholders. The results shown in Figure 3c reveal that more than 50% of the respondents never or rarely participate in planning meetings (S2.3). However, there is a widespread feeling that the management is committed to quality (S2.6), and only a minority of respondents feel like they are not encouraged to suggest possible improvements (S2.7).

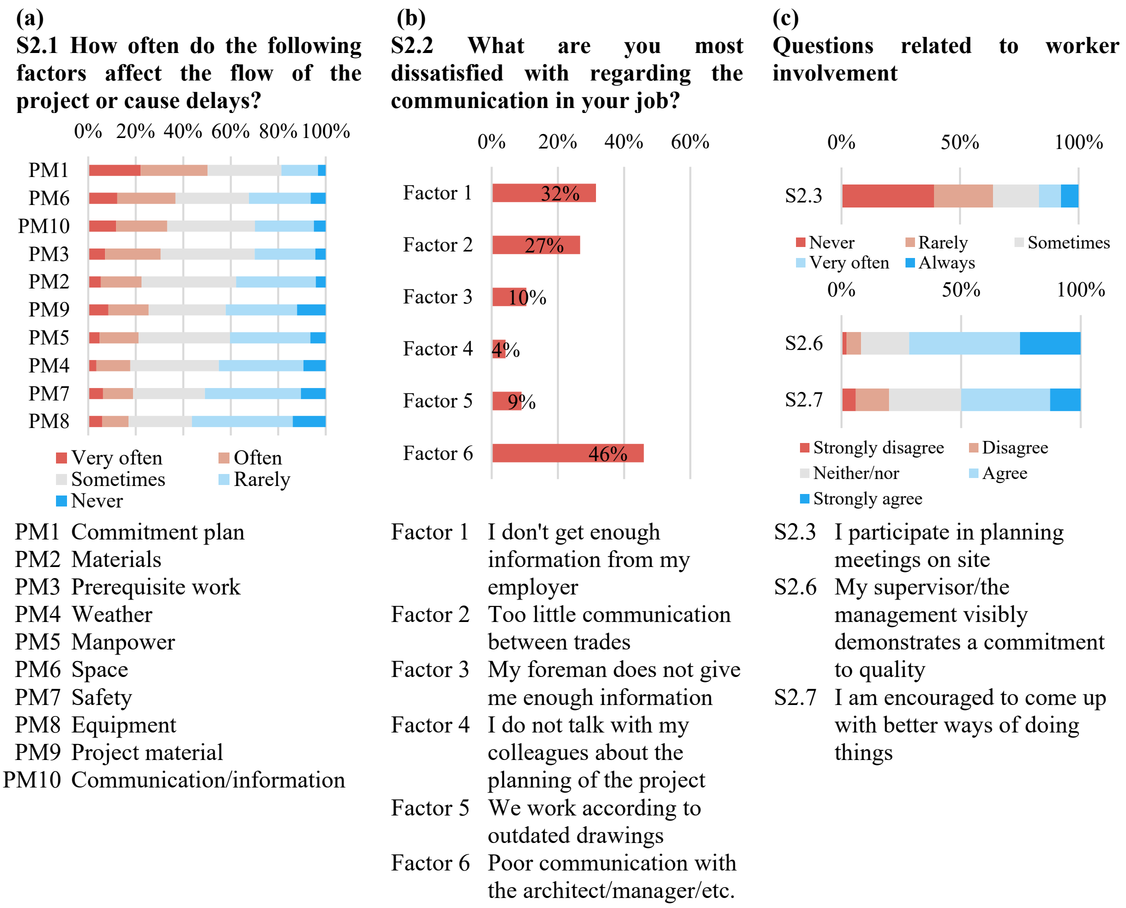

Figure 3: Results for Questions: (a) S2.1, (b) S2.2, and (c) S2.3, S2.6, and S2.7

The respondents were also asked about their knowledge of the project schedule and their own work tasks in the coming week and month. The answers are shown in Figure 4.

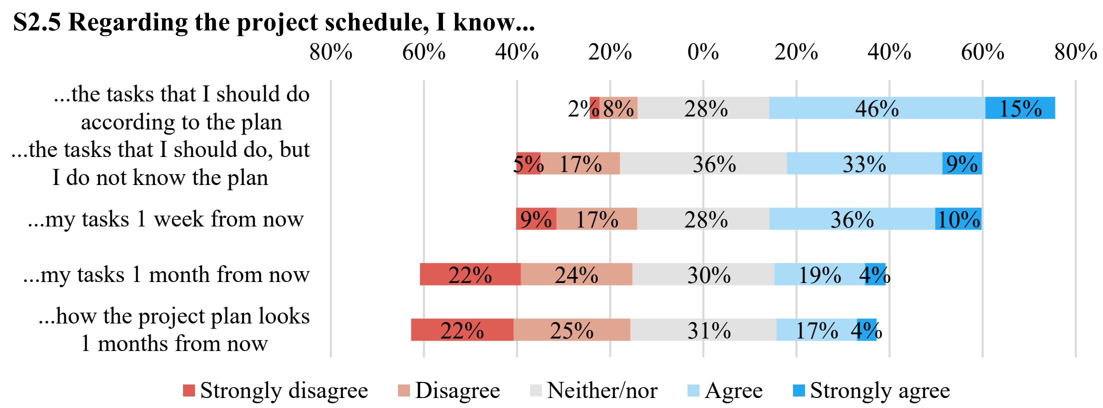

Figure 4: Results for Question S2.5

There is a significant difference in the respondents' knowledge about their imminent tasks compared to their tasks or the project plan in one month. While 46% agree or strongly agree to knowing about their tasks in the upcoming week, only 23% know what they will be doing in one month.

Figure 5 includes the results of questions related to the workers' perception of their time use. Almost half of the respondents (44%) feel they could use their time more efficiently (Figure 5a), and 57% feel that they waste 1 or 2 hours of their workday on unnecessary tasks (Figure 5b). This corresponds well with the result of S2.10B (Figure 5b) that shows 74% feel they spend at least half of their workday concentrating on their planned tasks.

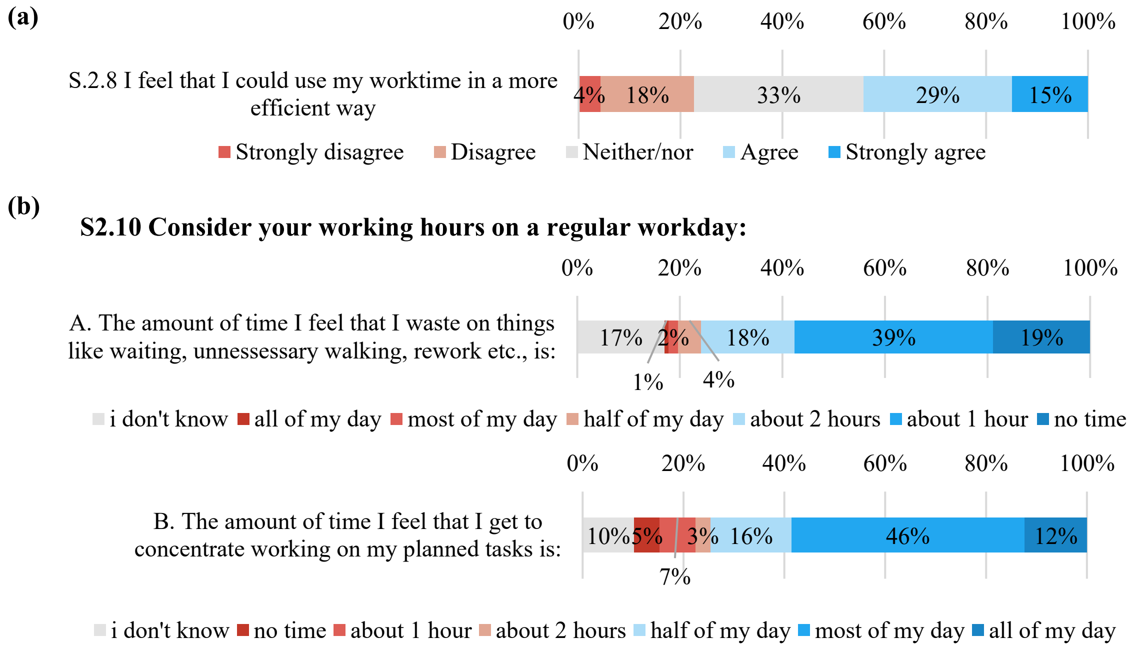

Figure 5: Results for Questions: (a) S2.8 and (b) S2.10 Concerning the Workers' Perception of their Work Time

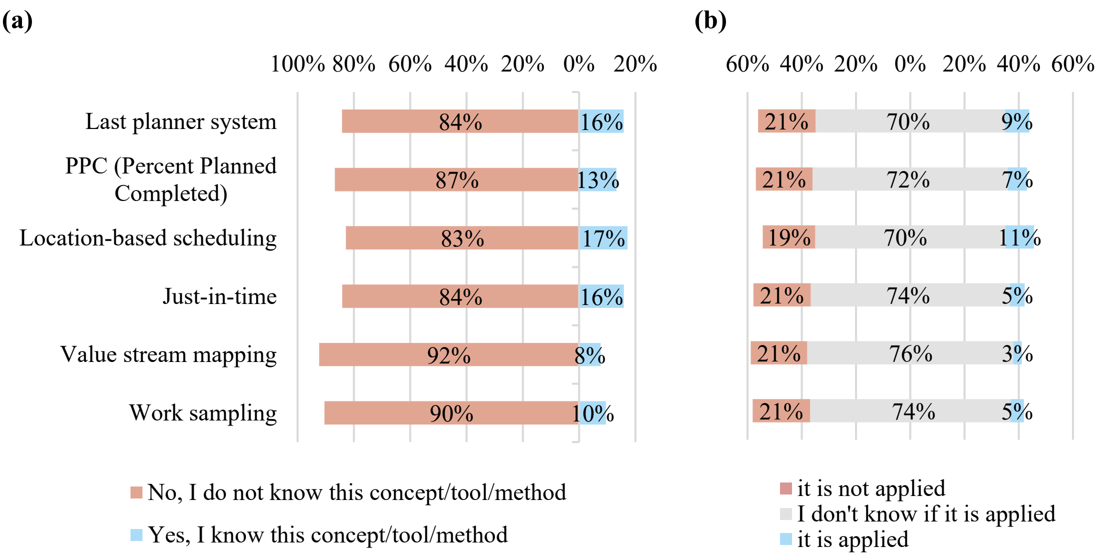

Figure 6: Results for Question: (a) S2.11 Regarding Knowledge, and (b) S2.12 Regarding Application of Lean Concepts/Tools/Methods

The PM section of the questionnaire was concluded with two questions assessing the respondents' knowledge of different Lean concepts/tools/methods (Figure 6). The answers are very clear; only between 8% and 16% of respondents know the six listed Lean concepts.

Consequently, the vast majority, between 70% and 76%, do not know if the concepts are applied in the project they are working on.

CONCLUSION

A high level of job satisfaction promotes psychological safety, which is crucial for workers to engage in learning behaviors and thus be able to improve their performance on construction sites. Psychological safety can be stimulated by acting in accordance with the lean principle of "respect for people".

This study presented a comprehensive job satisfaction survey, comprising aspects of project management, work environment, and health and safety. The survey was developed based on a literature review which included previous studies concerning surveys among workers. The review revealed nine recurring constructs. These formed the basis of the three aspects included in the present survey.

The survey was applied among construction workers on Danish construction sites. The results included in this paper focus on the project management part of the survey and are mainly descriptive. The most significant issues regarding project management are found to be unrealistic commitment plans and space and communication issues. The most dissatisfying factors among the respondents regarding communication are lack of information from their employer and poor communication with management. Most respondents never or almost never participate in planning meetings. However, they feel encouraged by the management to come up with better ways of doing things, which indicates that many employers are successfully creating challenging environments where employees are entrusted with authority, as suggested by Liker and Meier (2006) and Marksberry (2011). Another finding is that the workers' level of knowledge about the project plan and their own upcoming tasks is generally low when looking further ahead than one week. The results also clearly show that the knowledge of Lean concepts among construction workers in Denmark is very limited.

There is a large potential in connecting the survey results with the implementation of Lean on Danish construction sites (e.g., Percent Planned Completed), which did not fit within the length limit of this paper. This will be discussed in future publications.

Only a small part of the survey results is presented in this paper. Future publications will include more in-depth analyses of the results of all parts of the survey, including correlations of answers for different questions. Moreover, aggregated analysis based on demographic variables will be conducted, taking into consideration the impact of the demographic pattern of respondents.

The questionnaire developed for this study represents a tool that can be applied by other researchers and practitioners in other countries (template available upon request). This will provide opportunities to compare and learn from the differences and similarities in job satisfaction among construction workers in different parts of the world.

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FRAMEWORK OF INTERACTION BETWEEN ICT, PROCESS, AND PEOPLE IN CONSTRUCTION: A CASE STUDY

Vijayashree TM[1], Paramjit Singh Lota[2], and Bhargav Dave[3]

ABSTRACT

The construction industry is often criticised for lacking a holistic view on applying Information and Communication Technology (ICT) to improve project efficiency. Integration of the three core organisational aspects of people, process, and Information Technology (IT) must be realised to bring true benefits in construction project delivery. However, the industry has not yet reached significant maturity in achieving this synchronisation.

The research follows a case study-based approach where the authors were involved in the implementation of an ICT solution that helped streamline project planning and execution through effective collaboration on a Data Centre retrofitting project in USA.

The research demonstrates the importance of effective communication through efficient information management by deploying ICT which helped overcome inherent process inefficiencies and challenges on the case study project. Based on the observations, the authors have proposed a framework that highlights the interaction of ICT, people, and process, and mapped the results achieved on this project through their integration.

Keywords – Construction Management, Information & Communication Technology, Process Management

INTRODUCTION

It is a significantly evidenced fact that construction projects are still struggling to deploy well-structured processes and automated workflows and tend to resist adoption of technology (Dave et. al., 2008). While ICT has proven to enhance collaboration and integration amongst stakeholders, rigid conventional processes and latent information continue to prove incompetent in addressing the rapid changes in design and environment leading to catch-up planning (Martinez et. al., 2017).

While there is evidence that ICT adoption has enabled project performance by changing the processes, successful implementation of any tool or process requires acceptance and involvement by the people involved in the project (Dave & Koskela, 2009). Research has highlighted the importance of reviewing Business Processes with a need to focus on integrating people with change management for the successful implementation of IT in construction (Dave, 2017). However, there is not enough evidence on the nuances of team culture and process change that have helped in effective deployment of ICT to improve project delivery.

Past studies primarily comprise of individual cases where the success and/or challenges of adoption of ICT towards improving project efficiency have been documenting, while highlighting the importance of integrating the essential aspects of people, process, and technology. However, these studies are often limited to case-specific observations and conclude

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with the importance of integrations of the three verticals without any specific clarity or structuring on the "how". These studies provide limited exposure to readers in terms of extrapolating these learnings into a broader methodology or framework that can widen the spectrum of the observations while also providing clarity on the integration and interaction of these critical aspects. The paper here addresses this gap by utilising the observations from this case study towards developing a structured framework that can guide fellow practitioners to take the first steps towards integrating people, process, and technology effectively.

While ICT has played a crucial role in streamlining construction project delivery, the research here dives deep into understanding where the improvement stems from, i.e., the tools adopted, processes that structure and enable participation, and the project culture that drives interaction of people in the teams. The authors believe that a framework will not only guide the industry towards more effective deployment of ICT but will also help them better understand the nuances of their own observations through this structured approach as they deploy this on further projects.

LITERATURE REVIEW

Construction continues to remain a fragmented industry with each participating team bringing in their unique experience and technical expertise. Dave et. al. (2008) highlight the negative impact of this structuring on the project culture which tends to create friction between teams and isolation of information.

Information Management Systems (IMS) have proven to play a critical role in enhancing collaboration within projects (Craig & Sommerville, 2006). Nigel and James (2006) have highlighted the role of IMS in efficient collaboration between the Architect, main Contractor, and sub-contractor leading to successful delivery of an office refurbishment project. A cultural shift towards information sharing was developed through this integrated approach using IMS. Effective collaboration has helped drive efficient decision making for project planning and control (Dave et. al., 2014; Cheng et al., 2013).

ICT continues to help drive improvement and efficiency in construction project delivery. Ambuja et. al. (2013) discuss the use of ICT in providing historical information of previous jobs that helped balance the supply and demand for accurate daily and weekly planning for a mechanical contractor. Mobile tools have a direct impact on decision making efficiency through instant access to accurate and timely information (Harstad et. al., 2015).

Martinez et. al. (2017) have evidenced the benefits of visualisation from ICT in reducing lead time through improved communication from effective information sharing for a large-scale affordable housing project. Visualisation offered by 3D & 4D CAD technology has enabled teams to take effective engineering and design decisions (Khanzode et al., 2005; Rischmoller and Alarcon, 2005).

The characteristics of ICT play an important role in driving project culture in the right direction. Tools that enable participation through simplicity and ease-of-use enable information sharing (Dave and Koskela, 2009) which allows for better integration between project teams (McHugh et. al., 2019).

ICT also has the potential to provide completely disparate versions of the same truth when disconnected sources of information are left open to interpretation by teams in isolation. Effective deployment of ICT must ensure a cross-disciplinary capture and reflection of data across all project teams to develop a shared understanding of product-organisation-and process design (Fischer and Kunz, 2004). The interface between people, process, and IT are the critical points to ensure successful implementation of ICT in construction (Rischmoller and Alarcon, 2005).

The literature reviewed highlights the importance of accurate information exchange and efficient communication in the construction industry, and the role that technology plays in making the process more streamlined and effective. Inefficiencies are common across projects in the industry with a false expectation from technology to deliver instant benefits on projects. The fact is that cultural change and process alignment are the foundations for adopting any new technology (Harstad et al., 2015; Ahuja et al., 2009).

RESEARCH METHODOLOGY

The research is built on a case study approach where the authors were involved in the implementation of ICT (*VisiLean* tool for project planning, execution and monitoring) in the project. The authors helped deploy the ICT tool by working closely with the project management consultants appointed by the client for this project. The authors' participation on the project was in direct capacity through involvement in planning and review meetings while ensuring the tool is used effectively based on the project team feedback and discussions during these meetings.

The case study focuses on the critical factors of ICT for enabling efficient information exchange and effective communication with a keen focus on the accurate alignment of project culture and processes.

Based on their observations, the authors have developed a framework of ICT, people, and processes, to map the interactions and results documented on this. The intent of the proposed framework is to provide a matrix of reference for project teams exploring benefits from ICT, as well as allowing researchers and industry to further contribute to the framework by adding their observations and results from other ICT implementation.

CASE STUDY

The case study is of a retrofitting project at a major data centre in central San Francisco. The project involved the replacement of 10 Power Protection UPS (Uninterruptible Power Supply) units, that provide emergency power backup in the event of a sudden blackout (complete loss of power) or a brownout (temporary dip in voltage). These units are critical to ensure reliable 24x7 operation and protection of the hardware and file systems housed in these data centres.

The project client onboarded a project management and consultancy business in USA, with extensive experience of working on time-constrained, technically complex Data-Centre projects, cloud providers, and their supply chains, to help drive performance improvement through efficient project management methodologies that help streamline construction project delivery.

Various ICT solutions were adopted in this project, amongst which a tool called *VisiLean* was onboarded by the project management consultant for enabling collaborative planning and production control. The authors participated on this project by providing active support for the implementation of this ICT tool, *VisiLean,* by facilitating various collaborative planning and review sessions and working with the project team to ensure the implementation of ICT is aligned with their requirements.

PROBLEM DISCUSSION

The onboarding of an expert consultant along with the ICT solutions was a gradual approach towards overcoming the challenges specific to the project. The major challenges have been documented below to give context to the inclusion of ICT and the benefits achieved therein.

Installation of a new Product

The supporting contractors had no prior experience or background to install this type of equipment. With completely new configuration and operational procedures, without any guidance from the supplier, the team had to carefully understand and develop a strategy to transport, install, and test this equipment. This is also why the Client introduced an expert consultant with prior experience in working on mission-critical data centre projects.

Environmental Factors

The Data Centre was housed in the top-floors of a space constrained building in a congested street with limited access. Further, the Data Centre had to continue operations throughout the replacement of the units, maintaining uninterrupted service to customers across the globe customers. COVID -19 added further restrictions in terms of reduced manoeuvrability inside the building and additional cleaning of spaces and equipment, with stringent protocols to abide by. Simple operation of getting people in and out of the facility had to now follow specific paths and hallways, proving to be quite challenging.

Management of a diverse Team

The team deployed on the project had no past interaction or experience of working together. Everyone came with their unique culture with varying perspectives on technology. The different levels of exposure to ICT ran across a very wide spectrum – while some people were familiar with advanced 3D and CAD technologies, the others were still used to a paper-and-pencil approach. Further, while some teams believe in a data-centric project delivery approach, this team was more used to a people-centric approach, i.e., driven and lead by a key person who takes charge and defines the processes.

Information Management Challenges

With the onset of COVID and the limitations to physical interaction, the dependency on sharing information remotely increased significantly. Conventionally, the reliability of information the project team was presented with was also highly questionable. Further, the scope of information was also very limited, because of which a lot of assumptions would have to be made.

Due to a lack of common understanding between project teams, information was usually misinterpreted. Understanding of the problem statement varied across the project team, since there was no single source of truth, or common understanding of the data available. A combination of limited communication, lack of common understanding, and poor or inaccurate information led to ill-will and a culture of blame game. This created a toxic environment of negativity and uncomfortable conversations, which leads to people hoarding information.

It was difficult to collect everyone together physically in the same place at the same time. This led to limited interaction between project teams, leading to high social and trust barriers, limiting the scope for deeper, rich, conversations.

Problem Resolution with an Integrated Approach

Given the nature of the project and problems identified, the project team was pushed to evaluate ways to overcome these challenges to deliver the project within time and budget. Building on these challenges, the team was able to clearly define a set of requirements for which various ICT solutions were onboarded. Supporting this deployment was the expertise provided by the consultant that was able to curate the adoption of ICT with the right changes in processes by working closely with the teams at the ground-level to help build a culture of participation and good-will towards the project.

With the onset of COVID, the now dispersed project team shifted to connecting remotely by having their project meetings online. The teams could no longer be always present physically at the site for logistics planning as well. Online platforms were chosen to stay connected with the people as well as the site. Laser scans of the facility were used by the teams to virtually manoeuvre through the project site for accurate logistics planning by gaining a clear understanding of the environment challenges. The team was able to visualise the product and process design to develop an installation strategy with accurate information about the facility from these scans, and detailed specifications of the units to be installed. The project team had technical experts from Netherlands, Texas, Washington State, etc. who could join these meetings effortlessly. This helped the team accelerate the process of problem resolution and decision making.

To ensure effective information management even through remote connectivity, the teams deployed a Common Data Environment (CDE) where all project data was stored, barring financial information. Every project member was provided access to the CDE platform - Autodesk® BIM360™ a cloud-based platform which hosted design specs, facility layouts, etc. The intent was to democratise the information, ensuring everyone has access and visibility to all the project related data. The teams would mark-up 2D drawings, design documents, etc, for planning discussions and further information to develop a common understanding of the execution strategy. This was then discussed during the online meetings, so that the entire team was aware of the changes and the comments.

VisiLean, a cloud-based platform was deployed replacing Microsoft Excel® and sticky-note planning to collaborate with teams for accurate production planning, live monitoring of execution, and project control. With real-time updates from site on VisiLean providing clarity on work status, the team could take ownership of the tasks to be executed, and make any adjustments live with the entire team.

The visualisation of the production plan and the environment information gathered through the laser scans and live updates helped in understand the status of the job there. With synchronised information for everyone, the team was able to develop a common understanding of how the work can be executed in the best possible manner. Having this visualisation of information from ICT helped choreograph the sequence of event in sync between all trades with the right timing.

The team was able to drive efficiency in their use of project assets by understanding each phase and optimising the work and resources in sync to mitigate any risks. This approach helped provide evident savings in labour spend and direct cost to the facility owner.

Results Achieved

It is essential to evaluate the post implementation of such tools for continuous improvement. Hence, the implementation of these ICT solutions and process changes within the project team was evaluated to come up with the attained results discussed below.

- **Mistake proofing:** The team was able to limit human error and variability to ensure the project are developed as intended/designed. With ICT, the team moved away from a very paper and people driven approach which removed the heavy dependency on limited human resources for information. By reviewing the data live and together on a common platform, the team could come to consensus democratically. This proved to be transformational for the project by ensuring minimum surprises on-site and completely removing a blame-culture.
- **Information Transparency:** The project team utilised the CDE as the collection point for all project documentation – drawings, schematics, laser scans, etc. This helped develop the idea of one-team amongst the people. Once the team unravelled how one’s work impacted the other down the line, it made a huge difference in their approach to planning. This was done through transparency achieved from using VisiLean, which made these relationships clear and evident to the project team.
- **Visualisation:** Laser scans of the facility were added to the CDE to overcome the environmental constraints mentioned earlier. Project teams could access the entire facility though the scans remotely, visually survey and navigate through the spaces, to figure out the best way to approach the job. They could work out the ingress and egress accurately to work out the exact path for manoeuvring the equipment.

- **Single Source of Truth:** Having access to all this project information without gate keepers made it the single source of truth. In fact, the more people used it and contributed to it, the more information flew into it, thereby creating an approach of sharing, rather than hoarding information. The more one contributes to this information, the more valuable they become to the team, creating rich participation and collaboration.
- **Integration:** The teams would connect remotely using Zoom and other video conferencing tools that enabled them to work from their home offices. This way, even more data came flowing, with technical experts joining from Netherlands, Texas, Washington State, etc. The teams could leverage these tools for clear, valuable conversations, by looking at the same information – the single source of truth. This way, the team could develop a common understanding of the project, common reality, by clearly visualising what the challenges would be, mark them up on drawings, scans, and layouts using ICT, and do all of this remotely, saving the cost of bringing these experts on site. All this information would be transcribed back to the CDE as a captured log of discussed information, following which the tool would automate the process of disseminating this information to the relevant actors for further action.
- **Performance Improvement:** With the installation of each unit, the team was able to review their workflows for its successes and failures, from real-time updates captured on VisiLean from the project site. With this information, the team could review the scope for improvement and then discuss this analysis collaboratively to optimise the sequencing of activities for the next unit.
- **Collaboration:** The team was most successful in realising the importance of adjusting their processes according to the technology deployed. Their primary view was data, and to harness it most effectively, the team focused on revising their processes towards how the data was received, processed, and analysed. The teams started to overcome barriers to technological maturity by getting everyone together and developing a sense of comfort by discussing experiences and backgrounds. Once a level of trust was established, the introduction and absorption of the tools deployed on the project became less resistive.

PROPOSED FRAMEWORK & INTERACTION MATRIX

The results achieved on this project were a direct outcome of process and cultural changes adopted by the project team complimenting the deployment of the ICT solutions. To elaborate on these findings, the authors have proposed a framework that is built on the interaction between people, process, and technology towards streamlining construction project delivery through improved processes, better project culture, and ICT enabling these results.

From the case study, the value propositions attained from the people and process aspects, along with the various ICT solutions used on the project have been highlighted as a matrix of interaction in the proposed framework (Table 2). The interaction matrix acts as a frame of reference for the industry to apply on their projects towards overcoming specific challenges with the help of ICT, while coupling it with the right value proposition from the process changes and project culture.

The value propositions have been derived from the case study observations and results achieved. These have been then categorised by the authors between the aspects of people and process, based on their respective characteristics and alignment. For example, *clear communication* is an aspect of a *process* where information is structurally shared, while the *ownership of that information* cannot be guaranteed by the process; it is an aspect of *people* and their sense of responsibility towards that work and information.

Similarly, while a production management tool can prove to be very effective, it cannot guarantee *clear communication* till the *people* utilises the tool through an online meeting platform to discuss through *rich participation*. However, with *clear ownership*, the tool can guarantee a *sense of appreciation* for the *people* since their progress, work, and contribution is now clearly documented and visible to all.

It is through these various lens that the authors have layered this intricate framework of interaction together to map out a structured approach towards arriving at attainable project outcomes. While neither of the three components are exhaustive and all-encompassing, they are true to this project and a step towards their further applicability on projects across the industry.

Specific to the case study, the interactions have been mapped to highlight the benefits attained from the ICT adoption and the interaction of people and process therein. As an example, drawing on the adoption of a CDE platform, the project team was able to establish clear communication, democratise information and decision making, and understand the impact of work between trades. This helped develop a sense of appreciation, trust, and enable the contribution and ownership of information, which in turn created a positive work environment. This enabled complete information transparency between the project teams, thereby making CDE the single source of truth for the project.

Similarly, to overcome remote connectivity and limited access to the project site, the team used laser scans to develop a common understanding of the facility to help prepare for the logistic challenges by visualising the sequence of work better. This work clarity helped in reducing assumptions, thereby allowing the team to make effective decisions despite barriers to physical interaction.

The proposed framework is open to addition by the industry from their experience of value attained in processes and cultural aspects on their projects based on ICT solutions implemented. The goal of this framework is to offer flexibility and scope for further development in future research, by both industry practitioners, as well as fellow researchers.

Table 2: Framework & Interaction Matrix of ICT, Process, and People

ICT	VALUE PROPOSITION	Common Data Environment (CDE)	Markups on 2D layouts	Laser Scans	Online Meeting Platforms	Production Management Tool
PROCESS	Clear Communication	X			X	
	Democratising information & decision making	X	X			
	Understanding impact of work between teams	X			X	
	Shared view to problem solving		X			X
	Remote access to project site			X		
	Better work preparation			X	X	X
	Remote collaboration with teams				X	
	Accurate visualisation of flow of work			X	X	X
	Better assessment and review of performance					X
	Reducing variability		X			X
PEOPLE	Ownership of information	X				X
	Rich participation	X			X	
	Sense of appreciation	X				X
	Common understanding of project			X	X	X
	Builds more trust, Reduces blame culture	X	X			
	Selfless sharing of information	X	X		X	
	Reduces Assumptions, Clear decision making		X	X		X
	Overcoming barriers of physical interaction	X		X	X	X
	Willingness to improve		X			X
RESULTS ACHIEVED ON THIS PROJECT		Single source of truth Information Transparency	Mistake Proofing	Visualisation	Integration	Collaboration Performance Improvement

DISCUSSION

It is evident from the case study that the team deployed ICT towards streamlining construction project delivery by taking ownership of work, resolving clashes between work packages, and taking control over the risks posed by the project environment. However, it is important to note that the success is evidently credited to the adoption of the new processes offered by the technology, thereby marking a cultural shift. Some of the key points of discussion from the case study are listed below.

- **ICT enables trust and collaboration in the team:** A common platform enriched by information removes the barriers to communication and helps build an environment of trust and support. This is essential for teams to come together towards problem solving, rather than pushing the problem across one-another. While tools promise collaboration, it is important to understand that while technology does enable collaboration, it does so through the provision of accurate information that helps build the collaborative environment.
- **Renewing Processes is Key**: Adding technology on existing processes that haven't proven beneficial will just bring the processes to failure point a lot faster. ICT cannot do improvement on its own unless we allow the new technology to create new processes. With the right alignment of new tools with new processes, the team can enable an environment of least resistance to focus on driving efficiency in project delivery, rather than focusing on overcoming cultural resistance towards the new technology.
- **Technology is not a direct Solution:** Adoption of any new technology does not guarantee success unless the people are ready to make a cultural shift in their work processes. The key to enabling efficiency through ICT is the richness and accuracy of the information provided, the simplicity of its dissemination across the project team, and the ease of contributing to it. All these factors collectively contribute to define processes that support the technology adopted towards its full utilisation that finally helps to improve project delivery workflows.

While all three aspects are interconnected, interdependent, and equally important, the industry has struggled to integrate these effectively since decades. While it might not be a one-size-fits-all, a framework of this manner has the capability to offer the first steps towards understanding the nuances of these three aspects to then build on further.

CONCLUSION

The construction industry continues to be plagued by major challenges stemming from inefficiencies in its core processes. A significant credit for scope of improvement is given to the implementation of ICT in the industry. However, the notion of plugging in a tool and expecting improvement in overall productivity and benefits to the project and the team has proven to be a narrow perception in the industry. Previous research reinforces the drawbacks of this perception and necessitates the implementation of a holistic approach to streamlining construction project delivery.

This research addresses the misalignment of the three core organizational aspects of construction - ICT, process, and people, by proposing a framework of their interaction. Building on their observations and experience on the case study project, the authors map the interaction between the tools deployed and the value impact on the processes and team culture to highlight their complex interdependency.

The interaction matrix can be applied and referenced on other projects to further explore the value proposition from project processes and culture with the adoption of new tools and technology. The interaction matrix depicts how the three aspects function in sync with each other to achieve specific results that can help drive project performance.

LIMITATIONS

The authors acknowledge that the framework is built from a specific case study where limited tools under the ICT umbrella have been deployed with select participants and a set of value propositions have been studied. However, the authors would like to reiterate that this framework is built as a starting point for fellow researchers from the scientific community as well as industry practitioners to further contribute their observations and learnings to. This will help build the framework with more tools, more value propositions, and feedback from their teams to make it more effective and useful for the wider community in the construction industry.

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WORKER INVOLVEMENT STRATEGIES IN CONSTRUCTION: INSIGHTS FROM THE LEAN LITERATURE

Hugo Sefrian Peinado[1] and Dayana Bastos Costa[2]

ABSTRACT

The Human-centric approach concept establishes that human needs must be at the center of the production process. Human needs models propose a sense of belonging among these necessities since people require appreciation, collaboration, and involvement. In this work, the Employee Involvement (EI) concept relies on developing the workers’ sense of belonging to the organization and allowing these workers to change the work environment. Despite the potential contributions, papers systematizing EI strategies in the construction industry were not found in the literature. Therefore, this paper aims to identify worker involvement strategies in construction based on the EI concept in the Lean Construction literature. The research method adopted was a Systematic Literature Review (SLR). A total of 12 papers were considered eligible for this review. 12 EI strategies were identified and analyzed based on three constructs: upskilling workers, communication, and autonomy for decision-making. The results reveal that there are still few empirical studies. Furthermore, the strategies are based on the managers’ and researchers’ points of view, not considering the workers’ points of view. However, the presented strategies and discussion might be considered in elaborating and implementing the HC approach for construction. A set of questions was elaborated to support future research.

KEYWORDS

Employee empowerment, Employee participation, Industry 5.0, Lean construction 4.0.

INTRODUCTION

The human-centric (HC) approach is defined as placing the main human needs and interests at the center of the production process (Breque et al., 2021). Lu et al. (2022) bring a similar understanding, pointing out that manufacturing should be HC by positioning the well-being of the industry workers at the production process center. This concept is referred to as one of the cores of Industry 5.0 (Breque et al., 2021; Lu et al., 2022) and Lean Construction 4.0 (Hamzeh et al., 2021; González et al., 2023).

Lu et al. (2022) summarize the needs of workers in manufacturing based on the hierarchy of basic needs presented by Abraham Maslow in 1943. Wahba and Bridwell (1976) and Ward and Lasen (2009) also present other models that discuss human needs. However, the hierarchy proposed by Maslow (1943, 2017) is widely disseminated and used worldwide (e.g., Zhao et al., 2015). Furthermore, it refers to humans (Maslow, 2017), not specifically those who integrate an industrial sector. Thus, these aspects will also be considered necessities of construction workers.

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The five levels of human needs specified by Maslow (2017) are physiological (bottom), safety, love/belonging, esteem, and self-actualization (up). Based on this and in discussion with specialists, Lu et al. (2022) proposed the “Industrial Human Needs Pyramid”, also integrated into five levels, from bottom to up: safety, health, belonging, esteem, and self-actualization. Although this model needs to be analyzed to determine if it can be fully applied to construction workers’ context, this paper focuses on the third level, related to the need for belonging, presented in both models (Maslow, 2017; Lu et al., 2022). Lu et al. (2022) define the sense of belonging as human emotional needs for interpersonal relationships, affiliation, connection, and being part of a group. Some aspects of this need rely on appreciation, collaboration, and involvement.

Employee involvement (EI) is an important concept regarding this topic. Traditionally, employee involvement has two goals. The first consists of developing a sense of belonging to the organization through high commitment. The second refers to allowing the worker to change the work environment by giving suggestions that improve the organization's performance (Tortorella et al., 2021; Welikala & Sohal, 2008).

Employee involvement in the pursuit of continuous improvement has been widely discussed in the literature on operations management, industrial relations, work process, and human resource management (Hernandez-Matias et al., 2020). According to the authors, EI is a fundamental feature of continuous improvement programs.

EI has also been described as employee empowerment (EE) for decision-making and problem-solving at his/her organizational level (Tortorella et al., 2021; Welikala & Sohal, 2008). According to Sun et al. (2000), this understanding is based on the premise that the worker directly involved with a set of specific tasks is in the best position to decide and improve the process related to these activities. Another conceptualization proposed by Dimitmades (2001) highlights that empowerment refers to allowing and supporting the organization’s human resources to make efficient, effective, and high-quality decisions, leading to continuous improvement. Thus, Vidal (2007) emphasizes the need to increase the responsibility of frontline workers and improve their skills to perform these new demands.

Different terms can be found in the literature to which similar meanings were attributed, which are: involvement (Koskela, 1992; Hasle et al., 2012; Hernandez-Matias et al., 2020; Sun et al., 2000; Tortorella et al., 2021; Welikala & Sohal, 2008), empowerment (Koskela, 1992; Dimitmades, 2001; Vidal, 2007; Welikala & Sohal, 2008), participation (Sun et al., 2000; Tortorella et al., 2021; Welikala & Sohal, 2008), engagement (Liker, 2004; Hernandez-Matias et al., 2020; Tortorella et al., 2021) and commitment (Hernandez-Matias et al., 2020; Welikala & Sohal, 2008). This paper focuses on the first three terms presented since the last two terms also incorporate other meanings. Furthermore, employee, worker, and frontline worker are considered synonyms in this research.

The workers’ involvement has been a study subject by researchers in Lean Production/Lean Management (Beraldin et al., 2022; Hasle et al., 2012; Hernandez-Matias et al., 2020). Hernandez-Matias et al. (2020) named ‘soft-lean practices’ the ones aimed at workers' and managers' involvement and commitment to promoting the system's human aspects. The authors also emphasized that EI/EE are lean practices related to workers, using the terms employee's HRLP (human-related lean practices) to designate these practices. In the context of the Toyota Production System (TPS), Liker (2004) points out that the non-use of workers' creativity is a type of waste (a practice that does not add value). According to this author, this waste occurs when there is no use of time, ideas, skills, or opportunities for learning and improvement by not engaging or listening to workers. Among the 14 principles of the “Toyota Way” presented by Liker (2004), the sixth principle associates the empowerment of workers with continuous improvement.

Aligned with the lean literature, Hernandez-Matias et al. (2020) highlight that the involvement of workers for continuous improvement refers to organizational practices that, when implemented consistently, promote a constant increase in worker motivation and opportunities for improving products and processes.

Within the scope of Lean Construction, Koskela (1992) points out that the concept of employee involvement emerged from efforts aimed at Just-in-Time (JIT) and Total Quality Control (TQC). According to the author, there are several reasons for the empowerment of construction workers, including the need for quick responses to problems. Koskela (1992) also points out that continuous improvement depends on workers' daily observation and motivation.

Despite the potential contributions, papers systematizing strategies for employee involvement in the construction industry were not found in the literature. Besides, Noueihed and Hamzeh (2022) and González et al. (2023) raised important questions to be addressed by future research related to the social impacts of Construction 4.0, which are strongly related to the HC approach concept. One question regarding this review's topic is how to include/involve workers in the design and implementation of new construction processes.

Therefore, this paper aims to identify worker involvement strategies in construction based on the EI concept in the Lean Construction literature. Understanding the existing employee involvement strategies in the LC approach is essential for pondering possible paths to implement the HC approach in construction processes.

LITERATURE REVIEW

Involvement is not a technique but a philosophy that demands a transformation in how organizations are designed and managed (Dimitmades, 2001). As argued by Sun et al. (2000) and Welikala and Sohal (2008), for effective worker participation, it is necessary that responsibility in decision-making and the power and autonomy to act at their organizational level be delegated to these workers. Participation without attribution of power will result in unaccepted suggestions, leading to frustration and potential demobilization of workers in contributing to the organization's performance (Sun et al., 2000).

Welikala and Sohal (2008) and Dimitmades (2001) highlight two workers' empowerment tools available for application by managers: participatory management and self-management. In participatory management, workers receive partial authority and responsibility in decision-making and are encouraged to present their ideas for the organization's continuous improvement in all its aspects. In the case mentioned, implementing the ideas is up to the managers. In self-management, workers are given full authority and responsibility and held accountable for their actions. This autonomy and responsibility refer to presenting new ideas and implementing these proposals. The authors point out that the choice between these two tools will depend on the scope of responsibility and authority to be attributed to workers. Dimitmades (2001) highlights that total empowerment may not be appropriate for all organizations or workers. Thus, it recommends that managers conduct a comprehensive assessment to determine the empowerment strategy that best fulfills the organization's demands.

Despite the implementation of EI strategies being significantly frequent in manufacturing (Hernandez-Matias et al., 2020; Tortorella et al., 2021), the literature indicates a gap regarding applying EI strategies in construction and the systematization of the existing strategies (Lehtovaara et al., 2022).

RESEARCH METHOD

The research strategy adopted is the Systematic Literature Review (SLR). According to Dresh et al. (2016), SLRs are studies to map, find, critically evaluate, consolidate, and aggregate the results of relevant primary studies on a specific research topic. The gap found in the literature related to the systematization of EI strategies in construction was divided into the following question: 1) What are the strategies for upskilling workers to contribute to their participation in the design/implementation of lean processes in construction?; 2) How can communication between workers and managers be performed?; 3) How to assign responsibility and autonomy for decision-making to workers in the context of Lean construction? The research process is illustrated in Figure 1.

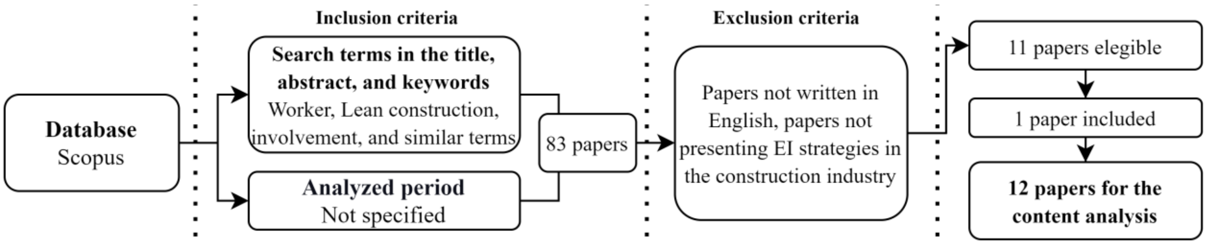

Figure 1: SLR research process adopted

The research process was composed of the definitions of the database, the inclusion criteria, the exclusion criteria, and the content analysis. The database adopted was Scopus since this search engine covers many journals and some proceedings related to construction management.

The following string was used as inclusion criteria: “TITLE-ABS-KEY ((employee* OR worker* OR workforce) AND (“lean construction” OR “lean production” OR “World Class Manufacturing”) AND construction AND (involv* OR empower* OR participat* OR engag* OR commit*))”. Papers on the subject were read to determine the most appropriate terms for the search string. Tests were made to select relevant terms and discard those that did not increase the number of publications during the search. No search period was specified. Eighty-one papers were identified at this stage.

Two exclusion criteria were adopted: discarding papers not written in English (due to the universality of the language) and not presenting EI strategies in the construction. From this stage, 11 papers were selected. If the paper presented only a part of the study addressed worker involvement strategies, the study was considered eligible for this SLR. A short paper that fulfills the criteria was also added, which was not located by the Scopus search.

The papers considered eligible for this review were analyzed and discussed based on three constructs highlighted by the scientific literature as important processes for EI: upskilling workers, communication, and autonomy for decision-making. **Upskilling workers** means improving their abilities to face new responsibilities (Vidal, 2007). **Communication** refers to improving the communication between managers and workers (Sun et al., 2000; Welikala & Sohal, 2008). **Autonomy for decision-making** refers to the attribution of responsibility to the workers for decision-making and autonomy for action at their level in the organization (Sun et al., 2000; Dimitmades, 2001; Welikala&Sohal, 2008; Tortorella et al., 2021).

RESULTS

The sample included two journal papers (16,7%) and ten conference papers (83,3%). Regarding journal papers, one was from the International Journal of Occupational Safety and Ergonomics (2021) and one from Frontiers in Built Environment (2022). Of the conference papers, eight were from the Annual Conference of the International Group for Lean Construction (IGLC) proceedings (2011, 2014, 2015, 2019, two in 2020, and two in 2021), one from European Modeling and Simulation Symposium proceeding (2017) and one from the International Workshop ‘When Social Science meets Lean and BIM Towards Industry 5.0’ proceeding (short paper) (2022). This section presents the content analysis.

The strategies identified in the lean literature for involving construction workers are presented in Table 1, divided into three groups: ‘upskilling workers’, ‘communication’, and ‘autonomy for decision-making’.

Table 1: Systematization of The Strategies Identified in the Analyzed Papers

Authors	Workers’ involvement strategies
Group 1: **Upskilling workers**	
von Heyl (2015)	Simulation game
Santana et al. (2017)	Educational animation
Hamzeh and Albanna (2019)	Training using non-digital games
Pütz et al. (2021)	Gamification components in LC training
Jacobsen et al. (2021)	Gaming environment involving multiple players simultaneously in virtual reality for LC training
Group 2: **Communication**	
Valente and Costa (2014)	Transparency practices at the construction site
Reinbold et al. (2020)	Digital visual management (VM) devices to increase workers' situational awareness (SA)
Abu Aisheh et al. (2021)	Constant and direct communication between managers and workers
Stevens (2022)	Worker anonymous Hazard Reporting app
Group 3: **Autonomy for decision-making**	
Antillón et al. (2011)	Autonomation in the context of safety
Reinbold et al. (2020) and Görsch et al. (2020)	Workers' situational awareness (SA) increased by digital visual management (VM) devices or other methods
Lehtovaara et al. (2022)	Decentralizing decision-making in production planning and control

UPSKILLING WORKERS

According to Hamzeh and Albanna (2019), all human resources involved with the process must be integrated, empowered, and trained to achieve all the benefits of lean construction. Thus, construction workers assume new roles and responsibilities and must be qualified regarding lean tools, principles, and concepts. von Heyl (2015) emphasizes the need for a systematic approach to teaching the basic lean principles and tools for the application of this philosophy to be accepted. Based on this understanding, the upskilling workers' strategies (group 1) identified in the literature are presented.

In order to teach basic Lean principles and tools to workers and site managers, von Heyl (2015) developed a systematic approach using a simulation game. A simulation of a road construction site was developed traditionally and also with the implementation of lean principles, followed by the participants' analysis. The results revealed that the simulation enabled the involvement of participants in the learning process. From the feedback provided by the workers, they felt motivated throughout the game, in which they were encouraged to experience the lean principles and reflect on possible improvements in existing processes. The author recommends that new tests be done to refine and use the proposed simulation game professionally.

Santana et al. (2017) worked on developing educational animation to transfer knowledge to workers regarding good practices related to lean construction. The material is structured for workers to have a vision of adopting lean practices in their work routine. As the authors point out, educational animation is a complementary action to training, as it illustrates how work should be carried out based on lean principles. The authors did not implement the proposed method on a construction site to collect feedback and improve the strategy. However, they encourage the development of new materials and the implementation of educational animation in future construction applications.

Hamzeh and Albanna (2019) developed a tool to assess construction workers' understanding of lean principles and concepts. A survey was conducted with workers from different construction sites to validate the tool and identify workers' weaknesses in understanding lean concepts. Based on the results, the authors proposed training for construction workers using non-digital games (House of cards, 5S number, and airplane game, among several others). The authors also present a correlation between the games with the lean categories explored in these games. According to the authors, training with games facilitates seeing lean concepts and principles applied, allowing workers to get involved with the learning process. Despite the suggestion of using games, the authors do not explore the application of these games in this paper to improve workers' knowledge.

Putz et al. (2021) also highlighted the need for efficient and targeted training to enable and motivate workers in applying lean construction methods (Last Planner System, Takt planning and takt control, 5S and A3). The authors conducted an exploratory study using gamification to improve training about lean construction principles and practices. The concept of gamification involves developing a game-like experience in a non-game context. Thus, gamification is applied by bringing game elements, such as scores, levels, and narratives, into the daily work context, creating a learning environment. The authors developed a framework for the application of gamification in LC training with several elements, such as challenges, cooperation, competition, feedback rounds, levels, points, rewards, and playing different roles, among others. They also highlight the importance of working with different elements, considering that different approaches in the game stimulate workers. The authors recommend that future studies be conducted using gamification in Lean Construction training to evaluate this strategy's contributions.

Jacobsen et al. (2021) proposed the development of a digital learning platform for teaching LC concepts using virtual reality (VR) with multiple players. As a result, VR can be used to teach lean principles and concepts in a more realistic environment when compared to using a board or other non-digital lean simulation game. In addition, the authors point out that the data collected automatically during the game can help in decision-making processes since it is possible to analyze this data. For future studies, the authors highlight the possibility that users can interact with each other within the game and also the need to implement new lean principles in the VR environment.

COMMUNICATION

Practices related to communication between managers and workers and the availability of readily accessible information for workers are part of the communication construct.

Valente and Costa (2014) developed a set of recommendations for applying transparency practices in construction based on a literature review and case studies. Among the 20 transparency practices applied, the authors concluded that 15 have an impact on the involvement of workers, such as exposure to long and medium-term planning, dissemination of short-term planning, Kanban systems, visual management boards, and quality indicators, among others. Increasing process transparency can be used for workers' motivation and participation, among other contributions. Some identified best practices were not implemented in the study but were suggested for future applications.

Reinbold et al. (2020) performed a literature review on the role of digitization in visual management (VM) to increase workers' and teams' situational awareness (SA). They highlighted using position sensors in tools, materials, and workers to collect geographic coordinates and present this information on displays in strategic places (e.g., floor entrances) in real-time. Thus, workers acquire situational awareness and can make decisions based on up-to-date information. The authors point out that future studies should be carried out to identify which VM devices could be used to display the information required in construction sites.

Abu Aisheh et al. (2021) studied the impact of lean construction principles on health and safety at work in construction projects. The authors point out that constant and direct communication between managers and workers seeking to avoid poor safety was the lean technique considered most important among respondents (in the subset related to communication). This communication can occur in daily joint meetings to improve the safety awareness of those involved. The authors indicated the limitation that the results refer only to the studied context, which may be different in other locations.

Stevens (2022) proposed a mobile computing technology for construction safety. The authors point out that workers feel uncomfortable reporting safety issues to supervisors in person. Therefore, a smartphone safety app was created, allowing the report to be done accurately and maintaining the worker's confidentiality. Although the beta version has been developed, it has not yet been tested on a construction site.

AUTONOMY FOR DECISION-MAKING

Strategies related to workers' or teams' autonomous decision-making are part of the autonomy for decision-making construct.

Antillón et al. (2011) proposed a matrix between LC and safety management practices to understand how lean practices interfere with safety. One of the results presented by the authors is the association between the concept of autonomation and the involvement of workers in the context of safety management at construction sites. According to Liker (2004), autonomation consists of not permitting a problem to pass to the next station by allowing machines or workers to interrupt production when something unusual is detected. Thus, Antillón et al. (2011) pointed out that autonomation can be directly extended to workers' involvement, indicating they can stop production whenever they feel at risk. Other Lean practices workers must participate in include root cause analysis, standardization, and continuous improvement. The authors reinforce the need for continuity of these studies to integrate safety as a target for production management.

The paper by Reinbold et al. (2020) is also included in this group since the authors discuss self-managed teams. The increased situational awareness using digital visual devices provides more appropriate decision-making for the context in which these teams are inserted. SA implies that teams have adequate levels of information to understand the project's status, which activities are in progress and where they are taking place, and the availability of materials and tools, among other information. These self-managed teams are formed of proactive workers capable of managing their activities and empowered to make decisions and introduce improvements in the process. The authors pointed out that the availability of data collected in real-time through digital visual management devices can be the link for construction workers to have greater autonomy in the decision-making process. They also highlighted that future studies should be conducted to understand which SA information should be available for different contexts. Görsch et al. (2020) conducted a literature review addressing SA for better decision-making for workers. The author investigated information capture methods and discussed how the outcomes would boost on-site productivity. However, as the authors point out, it is necessary to continue research to develop methods that explore the potential of SA.

Lehtovaara et al. (2022) proposed a framework combining decentralized decision-making with takt production involving frontline workers in construction. The main aim was to investigate how this combination could affect production planning and control (PPC) practices. In PPC construction, decentralization refers to distributing responsibilities related to production planning and control (initially centralized on project and site managers) to site teams (involving crew leaders and workers). The authors mentioned that intense involvement of the teams from the early stages of planning to the control phase is necessary for the decentralization of planning and production control to be successful. In the performed study, decentralized decision-making related to planning was partially dominated by crew leaders, with little involvement of workers. However, the authors report that decentralization in planning contributed to the commitment and motivation of the teams. In the control stage, there was a lack of worker involvement in decision-making. According to the results presented, the inadequate implementation of decentralization for decision-making in the control stage compromised the involvement of workers, causing them stress. The authors report the need for further studies, given that the present paper was limited to a single-case study.

DISCUSSION AND FUTURE DIRECTIONS

Although no time limit was established for the search, a few published papers discuss worker involvement strategies in the context of Lean Construction.

The group that refers to upskilling workers presents strategies exclusively to train construction workers to learn concepts, principles, and practices. Strategies involve simulation games, educational animation, non-digital games, gamification elements in training, and the application of VR reality for training. Based on the EI concept, new responsibilities are assigned to these workers, resulting in new demands regarding skills (Vidal, 2007). Thus, training has the potential to contribute to the improvement of workers' knowledge on the subject to fulfill these new demands.

Training using primarily non-digital games, educational animation, and gamification elements may have significant potential to be adopted to keep workers up-to-date with lean concepts, principles, and practices, improving their everyday work practices. Unlike the simulation or use of VR, implementing the first three strategies may be low-cost. However, generalizing what was pointed out by Pütz et al. (2021), it is necessary to analyze the effect of training using the mentioned resources in a structured manner to identify the actual contributions of these techniques in the learning and involvement of workers. As an example, the proposal by Hamzeh and Albanna (2019) involves the use of non-digital games for training workers. The authors did not evaluate which games are best suited to the workers' context, considering aspects such as the function performed by each of them, education, and familiarity with digital and non-digital games, for example.

None of the papers that integrate this group discusses what skills should be developed in workers to enable decision-making. The articles focus exclusively on understanding concepts, principles, and lean practices.

Regarding the communication group, strategies with different approaches were identified: using visual devices (non-digital or digital) to provide information to workers; bidirectional communication between managers and workers within the scope of safety management; and implementing a smartphone app for workers to report safety-related issues. Communication plays a crucial role in EI (Sun et al., 2000; Welikala & Sohal, 2008) since workers should propose improvements in the process. Thus, some discussions are provided as follows.

Communication is unidirectional in visual devices since workers only receive the information presented in the device (usually elaborated by managers). However, there is no communication from the worker towards the manager about improvements to be incorporated in the process, in the information representation of these visual devices, among others. Workers' participation in developing these devices can configure an interesting strategy. The worker will already be familiar with the interface and available information when using them daily.

Another aspect to highlight is that Abu Aisheh et al. (2021) do not present a systematized bidirectional communication strategy involving: the collection of workers' proposals and perceptions by managers in the field of safety; description of how these proposals are evaluated and incorporated into construction processes; how feedback is transmitted to the worker about the implementation or not of their proposals. The same occurs with the app's proposal to report safety-related issues, as it is not explicit how managers will use this collected information and how the general feedback process will be given to workers (considering that the reports are anonymous). The lack of a systematized strategy for integrating proposals and giving feedback will culminate in workers' demotivation and frustration, leading to a potential decrease in the presentation of their contributions to the organization (Sun et al., 2020).

Concerning the decision-making autonomy group, the following strategies were observed: application of autonomation in the context of safety at work; increasing situational awareness to improve the teams' decision-making; and decentralizing the decision-making process. Strategies for autonomy in decision-making represent, in the view of Sun et al. (2000) and Welikala and Sohal (2008), the effective participation of workers.

All the strategies presented involve decentralizing decision-making since this responsibility will not only be up to the project/site manager. Lehtovaara et al. (2022) mentioned that the benefits of decentralization and autonomy in the decision-making process had been the focus of interest in several production sectors, considering that this strategy contributes to increased efficiency, creativity, and well-being of workers. Despite the potential contributions observed in the literature, only Lehtovaara et al. (2022) conducted an empirical test of workers' involvement in decision-making. However, the strategies adopted in the study compromised the workers' effective participation in the production planning and control process. Thus, the latent need for developing effective strategies to ensure the involvement of workers in the decision-making process in different construction activities remains for future research.

In general, for workers to be involved in construction, there is a significant need to address efforts towards upskilling workers, communication, and adopting strategies that enable workers' autonomy for decision-making. These actions complement each other since adequate decision-making is only possible by increasing workers' skills and improving communication between managers and workers. Table 2 presents a set of questions that may help researchers advance studies on employee involvement based on the three constructs mentioned.

Table 2: Research Directions Based on the Three Constructs Related to EI

Construct	Questions to be addressed in future research
Upskilling workers	- What skills should be developed to enable construction workers to make decisions at their activity level? - How to develop the skills required for workers' participation in construction? - Which training strategies have the most significant potential to train workers in lean concepts, principles, and practices considering the characteristics of construction workers?
Communication	- How to systematically establish bidirectional communication between workers and managers to ensure workers' proposals for process improvements are collected, analyzed, and possibly incorporated into the organization's practices? - How to organize the feedback process to give feedback to workers on the implementation or not of their proposals? - How can workers contribute to elaborating visual devices (related to the principle of transparency) since they will use the available information on these devices? - How to establish interaction between managers and workers based on the information in the visual devices?
Autonomy for decision-making	- In which project production and safety activities can managers assign workers autonomy for decision-making? - What new responsibilities could managers assign to workers within the functions performed at the construction site? - What strategies should be implemented to guarantee the real participation of workers in the decision-making process without this participation being restricted to crew leaders? - How could workers be involved in decision-making at their organizational levels based on the knowledge and skills they developed and the communication strategies adopted?

Regarding the HC approach, Lu et al. (2022) point out that it is an early and unclear concept that needs urgent discussions to clarify its research agenda. Despite the concept positioning presented by the mentioned authors in the manufacturing industry, this concept still needs to be determined in the construction industry, demanding research to guide the comprehension and implementation of the HC approach in construction. Therefore, EI strategies in the context of LC have the potential to contribute to the elaboration and implementation of the HC approach in construction since placing the main human needs and interests at the center of the production process is a focus of both concepts/approaches.

CONCLUSIONS

This paper contributes to the body of knowledge by systematizing worker involvement strategies in LC based on three constructs: upskilling workers, communication, and autonomy for decision-making. In total, 12 EI strategies were identified and analyzed. Despite advances in discussions on the involvement of workers in construction in light of LC, there are still few empirical studies, mainly directed to autonomy for decision-making. In addition, the strategies identified in the literature are based on the managers' and researchers' points of view that workers must develop more knowledge and skills to participate and make decisions at their organizational levels. Further research should assess the workers' perception of how they can contribute to the organization based on their previously acquired knowledge, skills, and experience.

Based on the analyzed studies and the concept of EI, a set of questions was elaborated that can be considered for the continuity of reflections and strategy elaboration. The presented strategies and discussion might support elaborating on and implementing the HC approach. Regarding the use of digital technologies related to the Construction 4.0 paradigm in some of the identified strategies (e.g., VR and sensors), future research should also investigate how other technologies associated with this paradigm can contribute to workers upskilling, communication, and autonomy for decision-making.

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UNETHICAL AND CRIMINAL – PREDICTING “DARK SIDE” PHENOMENA IN THE AEC INDUSTRY

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ABSTRACT

This paper outlines prediction of “dark side” (illegal or unethical) phenomena in the AEC industry. “Dark side” phenomena pose a substantial yet unexplored threat to Lean Construction practices. Insights from criminology are used as a starting point for the analysis. A meta-study of the findings from a small research program carried out within the Norwegian AEC industry was conducted. It was enriched by an assessment of literature on crime prediction in criminology and on “dark side” phenomena in the AEC industry. Results show that predicting “dark side” phenomena in the AEC industry ought to take in temporality (when in the process challenges occur), value chain (who in projects are likely to act) and typology (what kind of actions are susceptible to occur). In addition, contextual factors (physical surroundings, geography, belief systems etc.) need consideration. Unlike criminology, predictions within the AEC industry cannot be based on AI approaches fuelled by historical data but need to be based on insights from construction process research. The preoccupation with “best practices” in the contemporary literature ought to be complemented with assessments of “worst practices” within all parts of the built environment. This is work largely left undone.

KEYWORDS

Anti-corruption, crime, ethics, prediction models, unethical

INTRODUCTION

Unethical or criminal behaviour takes many forms occurring in different contexts and phases in construction projects. Though rising, the interest in such phenomena has long been scarce in the project literature and within Lean Construction (LC) in particular. This lack of interest seems strange, given the influence such phenomena can have on LC. Gehbauer et al. (2017), for instance, maintain that concerning questions of corruption, “[l]ittle has been published or done to fight this in Lean research or practical Lean papers”. However, they continue, this is strange, given that “[t]he number one waste in construction is corruption”. Here, we place such phenomena under the umbrella “dark side”.

By using the term “dark side”, we explicitly follow the research agenda outlined in one of the most potent contributions within the field over the last years (Locatelli et al., 2022), for whom the “dark side of projects is any illegal or unethical phenomena associated with projects”. One of the main attractions of this definition is its broadness. Permitting to include “systemic,

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group, and individual wrongdoings", to be "appropriate for macro, meso, and microlevel studies in projects", and to include "wrongdoings external to projects that impact their performance or affect how projects are initiated, governed, managed, and executed at any level" (Locatelli et al., 2022). In sum, the term "dark side" denotes undesirable phenomena to be combatted.

Over the last decade, many authors have underlined the need for analyses of "dark side" phenomena within the field of project management. Jonasson and Ingason (2013) call it a "neglected area", whilst Walker (2014) lament the "dearth of papers" on the subject. However, the proposals for ethical reflection have been rather general and lack the precision needed for discussing real-life challenges. The question of potential measures has received valuable contributions though. Sichombo et al. (2012), for instance, provide the outline for third-party controls over project procedures. Despite lamenting the "paucity of research on anti-corruption measures", Lehtinen et al. (2022) analyse the effectiveness of different corruption prevention efforts reported on in the literature. In addition, ethical guidelines and normative documents specify points of contagion in which the AEC industry is particularly exposed.

It seems, however, that one crucial step is missing from the analyses carried out. To a certain extent, all prevention measures build on understanding how "dark side" phenomena occur within specific contexts. Given the significance of "dark side" practices within the industry, methodological tools for effectively anticipating unwarranted behaviour are in high demand. There is, in other words, a dire lack of a *crime prediction model* in the AEC industry. To address this challenge, the following research questions are addressed, 1) What would be the attributes of a crime prediction model within the AEC industry?, 2) What are the main obstacles to establishing such a model?, and 3) What research will be required to improve the proposed model?

In the following, we first outline "dark side" phenomena in the industry. Secondly, we argue for the need for a prediction model to be able to tackle these challenges. Thirdly, we seek input from other fields to outline a model. Fourthly, we propose a model adapted to the AEC industry before, finally, we discuss further research needed to establish such a model.

THEORETICAL FRAMEWORK

Eggen et al. (2017) estimate that not-reported turnover in the Norwegian AEC industry corresponds to approximately 28 billion NOK annually – just under 10% of the industry's total turnover. However, the analysis does not include counterfeit materials nor other criminal activities in the material chain, a figure Hastak et al. (2016) assumed to correspond to another 10% of the complete turnover of the AEC industry in the US. Given deep international links, it is likely that the Norwegian figures are similar. Research suggests that the Norwegian material chain is, in fact, the victim of significant fraudulent behaviour (Engebø et al. 2016; Kjesbu et al. 2017). In combination, it seems likely that non-reported activity in the Norwegian context comprises between 10% and 20% of the industry's total turnover, most likely closer to the highest number. In addition to this, other "dark side" phenomena that are clearly ethically doubtful yet not expressly condemned by law flourish; examples such as gaming (Skaarberg, 2016) and circumvention of contractual demands (Aure et al., 2020), are documented.

These challenges indicate that "dark side" phenomena significantly challenge contemporary AEC industry ventures. This is particularly true concerning lean approaches with flow and waste reduction as expressed core principles. Still, the literature on "dark side" phenomena within the LC literature, as in the IGLC papers available at iglc.net proves limited. A search for "crime" gave, for example, only three hits (Kjesbu et al., 2017; Aure et al., 2020; Lohne et al., 2021). Equally, "ethics" turned up three (Svalestuen et al., 2015; Drevland et al., 2017; Thameem et al., 2017), "collusion" only one (Stifi et al., 2014), price fixing none, whilst "corruption" gave six (Stifi et al., 2014; Stifi et al., 2017; Thameem et al., 2017; Daramsis et al., 2017; Rizk et al., 2018; Wold et al., 2019). The search function on iglc.net only considers the papers' titles, abstracts, keywords, and author names. Therefore, some other papers will discuss "dark side" phenomena (e.g., Gehbauer et al., 2017), without them appearing in the search results. However, few IGLC papers have "dark side" phenomena as their primary focus. This appears strange, given the attention to value creation within LC context (see e.g. Drevland et al., 2018), and that "dark side" phenomena pose significant challenges to value creation. Prediction models are key to address such challenges.

PARAMETERS OF PREDICTION IN CRIMINOLOGY

Developing a prediction model for "dark side" phenomena requires insights from other fields. The field of criminology is the arena where theoretical and practical trends can best be observed.

It needs remarking that contemporary work on prediction within the field of criminology is challenging to get an overview over. In particular, what concerns work based on advances in fields such as Artificial Intelligence (AI) and big data-driven approaches, much of the state-of-the-art work is published in conference settings rather than in journals. In addition, the implications of technological advances driving the possibility conditions for the field – face recognition, register data mining, and integrated surveillance camera systems – are challenging to assess for the non-expert. Finally, much secrecy characterises the advances in the field, as precise information can be sensitive to local and international actors with malevolent intent.

Still, this is where relevant prediction models are the most mature. The essential aspect of these – the parameters according to which prediction happens – is primarily fundamental and not determined by the influence of specific algorithms. Even though the approaches below concern solely crime prediction, they are directly relevant to "dark side" phenomena.

Shamsuddin et al. (2017) present an overview of the state-of-the-art of crime prediction models. They underline how analyses can be based on both qualitative – mainly scenario analyses – and quantitative methods. It is easy to agree with the authors' call for pluralism in approaches, given that "no standard method […] can solve the problems". Less convincing is the claim that the "biggest challenge facing crime prediction is how to efficiently and accurately analyse the increasing volumes of crime data". Given the lack of data characterising the analyses of "dark side" phenomena in the AEC industry, the most pressing area of concern within this context is developing the very foundations of such analyses. The following sections review the principal axes of analysis found in the literature.

Crime prevention depends on knowing what, where, when and under what conditions crime occurs – that is, prediction; Mansour and Lundy (2019) propose spatial and temporal aspects, in addition to weather conditions, play a significant role in crime – adequate for serving as prediction parameters. There are substantial challenges to the field. For instance, studies often lack a transparent reporting of study experiments, feature engineering procedures, and use inconsistent terminology to address similar problems (Kounadi et al., 2020). However, in our context, the principal approach to the analysis of prediction factors is of concern.

SPATIAL PREDICTION

The most prominent aspect of crime prediction appears to be the spatial dimension. There is a remarkable growth in spatial crime forecasting studies due to interdisciplinary technical work (Kounadi et al., 2020).

Several authors have underlined how crime and criminogenic factors are not homogeneous across space. For instance, Boni and Gerber (2016) highlight how crime is area-specific within cities. Furthermore, crime prediction models can be established based on statistics and machine learning techniques. Barreras et al. (2016) underline the efficiency of such approaches in their study consisting of geographical identification of areas with high crime frequency in the past to prevent future crime, relying on fixed determinants of crime.

The literature on crime prediction models sees going from the constatation of current crime (statistics) into future crime (prediction) as the critical challenge. For the case of Shamsuddin et al. (2017), as with several others, this conception stems from a relatively simple typology of crime, proposing that it can be "divided into a few types such as crime against properties (theft, burglary, and robbery) and crime of aggression (homicides, assaults and rape)". Based on this type of typological approach, quantitative prediction models can be construed. In other words, if input values are easily grasped, output values (the prediction) become a question of technique.

TEMPORAL PREDICTION

In a fascinating study, Zhao et al. (2022) expand on the spatial dimensions of crime by illustrating the existence of correlations among different types of crime from temporal and spatial perspectives. These researchers underline the potential for contemporary analyses based on big-data approaches to construct accurate crime predictions. Such studies have also been expanded to include demographic data drawn from mobile networks, showing the where's and when's of crime (Bogomolov et al., 2014). Ramasubbareddy et al. (2020) equally identify this interrelation between the spatial and the temporal, the analysis of which can serve to predict future crime in a specific location within a particular time. Several methodological approaches are suggested; for instance, Rummens et al. (2017) argue that so-called predictive analysis can be used to predict when crime will occur.

TYPOLOGY IN CRIME PREDICTION

The overall impression from the literature review is that current prediction models are oriented towards a relatively narrow band of "dark side" phenomena. For their multi-type analysis, for instance, Zhao et al. (2022) stick to seven types – burglary, felony assault, grand theft, murder, rape, robbery, and vehicle theft. Mansour and Lundy (2019) describe how "*spatial, temporal and weather features do indeed play a significant role in crime type classification – for example, drug crimes tend to happen on sidewalks, late in the evening and in cold temperatures*". Underlying social predictors – typically based on indicators of "concentrated disadvantage" (e.g., racial heterogeneity, poverty, and family disruption) – are found to be among the strongest and most stable predictors (Pratt and Cullen, 2005).

Some authors have argued against this predominant scope of prediction. One aspect of this concerns the superposition of predication parameters. Connealy (2020) found that risk factors for crime are not generalisable and that different types of crime need to be considered separately. This notion suggests that while considering different types of crime can improve the accuracy of crime prediction, risk factors for crime are not generalisable and need to be considered separately: «*risk factors are not generalisable across crime types or across cities. Researchers and law enforcement need to examine local, crime-specific contexts when assessing crime problems and generating solutions*». Another aspect concerns the very scope of the prediction effort. As Lavigne et al. (2017) underline, "*[f]inancial crime is a rampant but hidden threat. In spite of this, predictive policing systems disproportionately target "street crime" rather than white collar crime*".

EXTERNAL FACTORS

As maintained by Tang et al. (2019), traditional crime prediction models reveal the spatiotemporal dynamics of crime but tend to ignore the environmental context of the geographic areas where crimes occur. Towers et al. (2018) underline the need to consider external factors potentially influencing crime occurrence and type, mentioning "climate, daylight hours, day-of-week, and holidays and festivals". Not surprisingly, macroeconomic, demographic, and socioeconomic factors are found to influence crime rates (Hazra, 2020). For what concerns white-collar crime (significantly less discussed in the material examined), Sajid et al. (2011) identified peer support, corporate culture, lack of accountability and reporting as the most critical prediction factors. Others have proposed the inclusion of other contextual phenomena into the analysis, such as Bhattacharya (2013), who point to how differences in the religious composition of regions influence the occurrences of (at least certain types of) crimes. Still, approaches to this field lie at an exploratory level and are seemingly mainly concerned with simple phenomena – such as street-level misconduct.

KNOWLEDGE GAP

Rummens et al. (2017) underline, "*[p]olice databases hold a large amount of crime data that could be used to inform us about current and future crime trends and patterns.*" It is commonplace for the above-cited papers to suggest that incorporating data from multiple domains and using deep learning architectures may improve prediction models. In sum, as Garnier et al. (2018) maintain, "*[u]nderstanding how social and environmental factors contribute to the spatio-temporal distribution of criminal activities is a fundamental question in modern criminology*". The current response is to broaden the scope of data collection and to deepen the analytic techniques employed for prediction. Still, and crucial for the analysis here, is that tools for predicting crimes do not guarantee the avoidance of discrimination or bias due to human intervention when selecting the data that feeds into an algorithm.

The implication of such an insight for a prediction model for the AEC industry is that a proper understanding of the parameters of "dark side" phenomena within the industry is really the core premise for good predictions to come out. Such parameters are currently lacking.

Lohne et al. (2023) argue that the lack of an accurate understanding of the where, when, why, and how of "dark side" activities in the AEC industry leads governmental bodies and control authorities to focus their attention on only a limited part of the potential "dark side" phenomena actually or potentially occurring. Much of the literature discussed from the field of criminology discussed above has had relatively easily observable infractions as their object of analysis, such as street violence, drug dealing and theft. The "dark side" phenomena to address with a prediction model are more complex, and therefore, it is unlikely that we can apply contemporary statistical approaches to them. The knowledge gap is consequently twofold. First is the axis according to which a prediction model is to be operative. Second is the potential for prediction without recourse to statistical tools. Correctly understanding the parameters for prediction, therefore, becomes essential.

METHODS

The research presented in this article synthesises the results of a small research program carried out within the Norwegian context, "Mapping opportunities for criminal behaviour in the Norwegian BAE industry" (Kartlegging av mulighetsrom for kriminell adferd i norsk BAE-næring), supported by Project Norway. From 2014–2021, "dark side" phenomena in the Norwegian construction industry are analysed from a construction process perspective. Based on a prior scoping literature review (Lohne et al., 2019) and individual literature studies carried out for each of the research projects in the program, a new search for literature in Google Scholar and Scopus following the prescriptions of Yin (2015) was carried out.

The findings stem from a meta-analysis of peer-reviewed publications based on qualitative approaches. These publications were selected as they dealt with the spatial dimensions, the temporal dimensions, typology and/or external factors that could be used for crime prediction. The term meta-analysis is here not strict, with the use of statistical methods or based on series of structured reviews, but rather as outlined by Glass (1976) as an analysis of analyses. As such, the peer-reviewed publications are part of the outcomes of the research program. The publications identify responses to work-related crime from a construction process perspective. These responses concern both the identification of challenges and potential measures within the theoretical optic governing the research program.

The unit of analysis is the AEC-industry as a whole: The whole construction process from strategic definition to termination; the entire material supply chains, from primary producers to wholesalers, including how illicit materials enter the workplace; the supply chain, from clients to subcontractors carrying out the physical work on the construction site. In addition, the scope includes formal and informal rules and regulations concerning product and process awareness.

Given the magnitude of this unit of analysis, 22 peer-reviewed publications have been analysed in this meta-analysis. The potential for criminal activity in the Norwegian AEC industry is thus understood in a wide range of optics, varying from white-collar criminals to illicit workers at the construction site, potentially using below-grade materials in construction projects. It also highlights the role of rules, regulations, and ethical awareness among the actors.

For presentation purposes, the presentation of the crime prediction model here is static; in reality, the nature of “dark side” phenomena is dynamic, and the stages of the construction process where such undertakings take place vary (Owusu et al., 2019).

PARAMETERS OF PREDICTION IN THE AEC INDUSTRY

Lohne et al. (2019) broadly analysed the literature, identifying areas where research on “dark side” phenomena was relatively well established (in particular corruption), others where some research endeavours had been carried out (e.g. materials management/supply chain management), and again others that had gained surprisingly little attention (e.g. gaming and identity fraud). Still, based on what is described, sufficient evidence seems brought to the fore to establish a prediction model based on a parametric understanding of “dark side” phenomena in the industry. Still, no discussion on what parameters of analysis a “dark side” prediction model for the AEC should use was found. This chapter aims to outline an understanding of such parameters based on an assessment of insights from the general research literature and the research program. Even though inspired by insights from criminology as presented above, the proposed approach is not based on statistical models, but on insights from construction process literature on where challenges typically arise. This analysis is buttressed by comprehensive if not statistically valid empirical investigations (see also Lohne et al., 2023).

SPATIAL “DARK SIDE” PHENOMENA PREDICTION – VALUE CHAINS

The value chains play a role in “dark side” phenomena, and the value chains change during project phases. Ichniowski and Preston (1989), for instance, found that criminal activity can persist in the construction industry because of barriers to entry in certain markets and because of industry characteristics such as constant changes of work sites and restricted access to them.

Lohne et al. (2019) claim that the number of actors benefitting from crime in the AEC industry is surprisingly high. Owners, as well as main contractors, reap substantial benefits. However, legally organised workers, FM personnel and society tend to lose from such activities. White-collar workers tend to benefit and initiate activities related to the “dark side”, while blue-collar workers at entry-level positions mostly lose. However, even though the blue-collars can lose, they also seem to experience benefits. Both Gunnerud et al. (2019) and Evjen et al. (2019) registered a continuous recruitment of newcomers that was difficult to prevent. However, countermeasures were perceived as easy to circumvent. In addition, the contractors and project managers – who hired illegal immigrant workers, avoided taxation etc. – perceived the probability and consequences of being caught red-handed as small. Øversveen et al. (2022) identified an opportunity space for criminal behaviour in construction projects – for quality assurers, among others – due to high workloads and a high level of trust. A positive outcome with limited risk and a high level of trust can explain the existence of the “dark side” phenomena.

TEMPORAL "DARK SIDE" PHENOMENA PREDICTION – PHASES

A general insight from the research program and the international literature is that crime in the construction industry is most common during specific phases of construction projects. Given the "myriad activities" encompassed at separate phases of the construction process (Owusu et al., 2019), the notion that "[d]ifferent ethical issues […] arise at different stages of the project life cycle" (Jonasson and Ingason (2013:16)) is a view that resonates within the literature.

Several authors also underline that different phases in the process are prone to different types of "dark side" phenomena. This insight can be used as an analytic tool to search for the occurrence of specific types of "dark side" phenomena within different phases of a construction project. Kankaanranta and Muttilainen (2010), for instance, found economic crimes in the construction projects most common during the bid evaluation and tendering phases. Bowen et al. (2012) found corruption prevalent during project bid evaluation and tendering phases. Owusu (2019) found corrupt practices to be most common at the pre-construction stages. In fact, the prevalence of corrupt activities at early stages is repeatedly maintained.

Less seems to have been done to explore the characteristics of the different phases as enablers of "dark side" phenomena. In the research program, several papers examine how phase characteristics are enablers, notably at the design phase (Lohne et al., 2017; Svalestuen et al., 2015), in operations (Gamit et al., 2022), at handover (Lohne et al., 2020), at project termination (Iversen, 2020) and in phase transitions (Selvik et al., 2022). Among the findings is that sets of challenges correspond to different phases and that these are predictable to a certain degree. For instance, introducing illicit workers to the construction site is common immediately before handover. Firing et al. (2016) found that right before the handover of a shopping centre – when a need for speeding up the finishing activities appeared at the same time as all workers were working overtime – the construction site was chaotic and easy to exploit.

TYPOLOGY IN "DARK SIDE" PHENOMENA PREDICTION

There have been several attempts to establish (some sort of) a typology of "dark side" phenomena. The Chartered Institute of Building (CIOB), for instance, used quite a broad view of crime in the AEC industry and included the following themes in their list of phenomena (CIOB, 2009), notably theft, vandalism, arson, fraud, bribery, intimidation, assault, racketeering, illegal drug dealing or use, health and safety neglect, forced labour, illegal working, kidnap, illegal waste disposal, identity theft, data loss/theft, and handling stolen goods. Davies (2022) found that construction industries provide significant opportunities for criminal and harmful practices; including fraud, tax evasion, poor health and safety, and underpayment of workers. Kankaanranta and Muttilainen (2010) found that economic crimes were committed in the construction industry and mainly were related to dealing in receipts. In addition, phenomena such as collusion, corruption, and other types of organised crime are not included in the list from CIOB (2009), even though these have long been recognised as constituting significant challenges to industry practice (e.g. Locatelli et al., 2017; Thomas, 1977).

Complementing these, Bowen et al. (2007) also outline common types of criminal behaviour and add to these a set of unethical behaviours – collusion, bribery, negligence, fraud, dishonesty and unfair competition. Shah and Altabi (2018) continue this effort, listing unethical practices identified including untimely legal action, changing project manager's responsibility and delays in payment processes from the owner/client perspective etc. Though being numerous in their listing of unwarranted activities, the overall impression from the literature review is that current interest is oriented towards a relatively narrow band of "dark side" phenomena.

In addition, few authors discuss the systematicity of the "dark side" phenomena occurring. Certain exceptions to this exist; not surprisingly, this is typically the case of studies concerned with organised crime within the industry. An example of this is Thomas (1977), identifying theft of heavy equipment from construction sites as an organised, systematic, criminal operation sustained by contractors. In particular, there is a lack of literature seriously discussing the interrelationship between types of crime and AEC industry characteristics. Exceptions to this are Reeves-Latour and Morselli (2017), with their description of how bid-rigging activities are feasible through conspiracies (politico-business) organised around public construction bids. Equally, Hertog (2010) explains how public construction works are vulnerable to collusion.

The individual publications from the research program report on several types of "dark side" phenomena. Though the nature of counterfeiting limits the accessibility to data, Engebø et al. (2016) still identified counterfeit materials as a well-known problem in the AEC industry that had received limited attention in the literature. Kjesbu et al. (2017) identified widespread knowledge about counterfeit and substandard steel products among a relatively random selection of construction project participants. Richani et al. (2017) found that contractors who employ labour immigrants with false identities, launder money, and avoid paying taxes achieve a competitive advantage over legit contractors.

EXTERNAL FACTORS IN "DARK SIDE" PHENOMENA PREDICTION – CONTEXT DEPENDENCY

In parallel, the development of analyses of increased precision has been observable. This concerns, for instance, an increased interest in context dependency (e.g. Locatelli et al., 2017, on the exposure of megaprojects to corruption issues).

Still, external factors have not seen significant interest from the research community. Based on the experience gained through the research program, the suggestion is that such factors ought to include owner characteristics, contract regimes, geography (both centre/periphery and other human geography factors such as gender, ethnicity, class issues, educational levels, homogeneity/not and stability/flux). Anecdotal evidence exists; in Norway, there is a predominance of "dark side" phenomena detected in the most densely populated south-eastern region; still, this is where most of the police control activity has been situated – the reliability of the figures is low. Until such factors are properly examined, it is difficult to assess the role of external factors in AEC industry projects.

Findings from the research program reveal that projects cannot be studied without regard to their context dependency. Engebø et al. (2018) found that contractors – on the outside – clearly distance themselves from work-related crime and actively prevent criminal actors from entering their projects. However, the year before Engebø et al. (2017) found that the 50 largest contractors in Norway – of which only 19 had official ethical guidelines – struggled to close the gap between operating "legally and unethically" and "legally and ethically". As a result, there seems to be room for manoeuvre for many roles in construction projects. For instance, Wold et al. (2019) found that officials issuing building permits can go far without stretching the authority delegated to them. Despite extensive contractual and contracting measures in two airport development projects, Skovly et al. (2017) found that "dark side" phenomena will probably exist as long as someone benefit.

DISCUSSION AND CONCLUSION

This paper has addressed three research questions, notably 1) what would be the attributes of a crime prediction model within the AEC industry? 2) what are the main obstacles to establishing such a model? and 3) what further research will be required to improve the proposed model have been the three research questions addressed. Given the the analysis, the answers to the questions are inconclusive, yet point towards future analytic pathways.

Firstly, the analysis has shown that a crime prediction model for the AEC industry based on statistical approaches is unsuitable. Rather, there is a need for an analytic approach taking for starting point industry characteristics. The above analysis illustrates how insights from the field of criminology might serve as the foundation for a prediction model for "dark side" phenomena within the AEC industry. Secondly, the examined literature illustrates how parameters such as place, time and the combination of these serve as input to advanced modelling approaches. Still, as Shamsuddin (2017) points out, there are limitations to current accuracy of prediction. The main obstacle to such a model is to render it operationalisable. Prescriptions of simplicity, transparency and relevance are challenging to apply. In addition, given the lack of data, statistical models are of little help; prediction within the AEC industry needs to be based on analytic models, that is, insight into the very workings of the industry. Thirdly, what is presented in this paper is exploratory work, and the following analysis must be assessed with the clear need for such a model in mind. As described above, the processes prescribed by LC literature and practice are hampered by "dark side" phenomena – to a more significant degree than what is acknowledged. Further, the literature clearly states that the prevention methods employed today by police and other controlling agencies are far from achieving what is wished for. Future research should explore practical approaches based on the parameters identified to improve these practices, including deepening the understanding of these parameters.

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INVESTIGATING AND SIMULATING COLLABORATION AMONG THE LPS PHASES

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ABSTRACT

Although heavily studied, collaboration in construction is still perceived as an elusive or intangible aspect because of its complex nature. Its complexity roots in the unfeasibility of quantifying it or its impacts on the performance of a construction project. While some studies acknowledged the need to evaluate or assess collaboration, empirical and numerical methods that pertain to direct quantification of either collaboration or the impacts of collaboration on the performance of a project are still unaddressed. This paper aims to address this gap from a Lean perspective by investigating the effects of collaboration throughout the different phases of the Last Planner System. After a thorough analysis of the collaborative points occurring in each phase, computer simulation is employed to model the progression of a construction project from pull planning to lookahead planning and finally to execution while also modelling collaboration among the project members. Findings on how collaboration during each phase impacts the project performance differently are presented. This study's contribution lies in highlighting the importance of early collaboration in construction projects and emphasizing the need for accurate quantification of such qualitative aspects.

KEYWORDS

Collaboration, Last Planner® System, agent-based modelling, and simulation.

INTRODUCTION

Construction projects are often described as unique and complex due to their ever-changing methods, distinctive objectives, and uncontrollable factors (Howell 1999). Among these are labor factors such as supervision, incentive schemes, leadership skills, overtime, and worker interactions (Jarkas and Bitar 2014). Interaction in construction includes collaboration and cooperation, which (Schöttle et al. 2014) attempted to distinguish between. Their study described collaboration as "an inter-organizational relationship with a common vision." In contrast, cooperation was described as "an inter-organizational relationship among participants of a project, which are not commonly related by vision or mission". This paper will address collaboration, where project participants collectively strive to successfully complete the project.

One of the significant enablers of collaboration is Lean construction, along with its tools and techniques. The Last Planner® System (LPS) is one Lean tool (Ballard 2000) that not only fosters but also entails collaboration as a vital component for the success of its implementation. Developed to improve workflow and increase reliability in construction planning, the LPS is a production control system widely used in construction projects (Ballard 2000; Ballard and

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Howell 2003). It may be described as a mechanism for transforming work that "should" be done into work that "can" be done, then into work that was actually "done" (El Samad et al. 2017). LPS includes four main planning phases: (1) Master Scheduling, (2) Pull Planning, (3) Lookahead Planning, and (4) Weekly Work Planning (WWP).

While collaboration in construction generally and the LPS specifically has been frequently promoted, attempts in quantifying it have been limited to identifying its influencing factors through surveys and questionnaires. However, the direct quantification of either collaboration or the impacts of collaboration on project performance is still unaddressed. Therefore, this paper aims to highlight (1) the importance of investigating and accurately quantifying the impacts of collaboration on construction projects, (2) the change in the impacts of collaboration when occurring during the different LPS phases, and (3) the importance of early collaboration in construction projects. To achieve these objectives, a discussion over how collaborative points manifest in the different LPS phases is carried out, followed by agent-based modelling and simulation of the project members and tasks during the progression of a construction project from pull planning to lookahead planning and finally to execution. In the simulation model, collaboration among the project members throughout the different phases is also modelled and manipulated to study its impacts on performance. Finally, an analysis and discussion of the results are presented, and conclusions and future recommendations are suggested.

RESEARCH METHODOLOGY

A simulation-based research (SBR) approach is adopted to achieve the mentioned objectives. SBR may be divided into two methodologies: (1) research on the efficacy of simulation as a training methodology and (2) research using simulation as an investigative methodology (Cheng et al. 2014). This study follows the latter methodology to address research questions whose answers are unattainable through real-life experimentation without being too expensive or time-consuming. Therefore, after a rigorous discussion of the collaborative points in construction planning and in the LPS, collaboration is modelled through computer simulation and its influencing factors identified in the literature. Different scenarios depicting the different collaborative practices along the LPS phases are simulated, and their results are analyzed to deduce where collaboration has the most substantial impact on the project.

COLLABORATION IN CONSTRUCTION PLANNING

As collaboration is one of the "Five Big Ideas" presented by (Macomber 2004), along with optimizing the whole, coupling learning with action, viewing projects as networks of commitment, and increasing relatedness, collaboration must be investigated through the context of LPS to weave and embed its implementation from within. (Schöttle et al. 2014) defined collaboration and compared it against cooperation sometimes used interchangeably with the former. Among the presented definitions of collaboration was the phrase "the process of shared creation" (Schrage 1995), where several individuals with "complementary skills" engage in an interaction that creates a newly achieved understanding (Schöttle et al. 2014). Other researchers have defined collaboration as "a process of joint decision-making among key stakeholders" (Gray 1989).

Several studies investigated key strategies for effective collaboration in construction, such as one by (Shelbourn et al. 2007), who identified people, business, process and procedure, and technology as driving factors for successful collaborations. Moreover, a sense of familiarity, willingness, and level of engagement were described by (Skinnarland and Yndesdal 2010) as a set of collaboration indicators that describe the collaborative development process. Based on their study, all three indicators may have a positive functional relationship with the degree of collaboration in construction projects.

Collaboration has been a topic of interest for several researchers, each addressing it from a unique perspective, as it is essential for the success of any construction project. A study by (Jara et al. 2009) adapted a methodology called Extreme Collaboration in an AEC project to accelerate the design process of a multidisciplinary team that must optimize the architecture, structure design, energy efficiency, and cost of wood houses simultaneously. They also suggested a methodology for integrating Extreme Collaboration in the Pull Planning phase. Another study reviewed and analyzed the experiences of project managers and foremen with implementing the Last Planner System on a construction project from a collaborative perspective (Skinnarland 2012). They found that one of the most prominent outcomes of the LPS implementation was the establishment of an arena for collaboration. (Schöttle and Gehbauer 2012) showed the importance of a working incentive system to foster collaboration among project members and presented a model for managing such a system. (Abdirad and Pishdad-Bozorgi 2014) highlighted the importance of collaboration on participants' success in an Integrated Project Delivery (IPD) system depends. They proposed developing a framework of metrics to assess collaboration in IPD by investigating the traits of collaboration in IPD and linking them with respective metrics. Most recently, (Malvik 2022) viewed collaboration from an entirely different lens by putting the collaborative style of a successful football team in a Lean construction context. They conceptualized the ideas a famous football coach brought forward by viewing them from a Lean construction perspective and investigated whether collaboration techniques from another performance environment can inspire the Lean construction theory.

MEANS TO MEASURE COLLABORATION IN CONSTRUCTION

Collaboration may be perceived as an intangible or qualitative concept whose measurement may not be as feasible as other concepts in a construction project, such as productivity, budget, schedule, accident rates, and so on. However, some attempts at measuring or quantifying collaboration in construction were introduced, such as the one by (Abdirad and Pishdad-Bozorgi 2014), where collaborative traits within Integrated Project Delivery (IPD) are investigated and linked with respective metrics. A framework based on the identified traits and metrics is developed to achieve a proactive collaboration assessment within IPD. Identified traits included co-location of the project team members, diversity in skills, education, or organization roles, team productivity, the cost impact of collaboration, training, communication methods, and individual human aspects such as absence rate and turnover. Another study by (Marek et al. 2015) recognized the need for evaluating collaboration and presented a seven-factor model of effective collaboration alongside the Collaboration Assessment Tool (CAT), which the U.S. Department of Agriculture developed to evaluate partnership processes and identify key factors to successful collaboration. The seven factors were adopted from a study by (Mattessich and Monsey 1992) and included Context, Members, Process and Organization, Communication, Function, Resources, and Leadership. The developed model included a Likert-scale questionnaire, where participants were asked to rate several items of the identified factors. (Thomson et al. 2009) also relied on a questionnaire-based approach to "measure" collaboration among organization directors. Their guiding dimensions were Governance, Administration, Organizational Autonomy, Mutuality, and Norms. Collaborative planning is a vital aspect of construction projects, and Elsayegh et al. (2021) introduced the Collaborative Planning Index (CPI), a holistic rating system that considers all factors influencing collaborative planning. The CPI offers tailored experiences and strategies to improve collaborative planning practices, contributing to the body of knowledge on the subject. Partially implementing LPS can also yield positive results, as observed by Priven and Sacks (2013), who found that LPS fosters social networks among subcontractors, enhancing communication, reliability, trust, and coordination. Duva et al. (2022) compared the network topologies of two Architectural, Engineering, and

Construction (AEC) project teams to identify how network parameters impact knowledge transfer and project outcomes. Additionally, Cisterna et al. (2018) examined the suitability of Social Network Analysis (SNA) in the AEC industry and identified the influence of project complexity and cultural aspects. Lastly, Lagos et al. (2022) studied the LPS adoption levels, team collaboration, and project performance by comparing two Chilean construction projects, finding that mature LPS adoption significantly aids collaboration and performance. While these studies introduced a much-needed perspective on how collaboration may be assessed and evaluated, empirical and numerical methods that pertain to the direct quantification of either collaboration or the impacts of collaboration on the performance of a project are still unaddressed.

COLLABORATIVE ACTIONS IN THE LAST PLANNER SYSTEM

This section will discuss the LPS phases and the various tasks that constitute each LPS phase, followed by an investigation of the different collaborative actions that enable each task's success and effectiveness. The Master Schedule phase is a crucial aspect of the Last Planner System (LPS) in construction project management. This phase involves creating a high-level project schedule that provides an overview of the entire project. This schedule aims to help the project team understand the critical path and identify potential constraints that could impact the project timeline. The Master Schedule is typically created at the start of the project and is based on the project scope, resources, and constraints. It shows a high-level view of the project timeline, including major activity start and end dates and dependencies between activities. During this phase, the project team should also identify the critical path and any constraints that could affect the project timeline. The Master Schedule is then used as the basis for the Pull Planning and Lookahead Planning phases of the LPS. As one main principle in the LPS is planning in greater detail as you get closer to execution (Hamzeh and Aridi 2013), Master Scheduling includes setting major project milestones and highlighting deliverables to release once the milestone is complete. It also ensures that the perspectives of various project partners for each milestone are aligned (Hamzeh et al. 2009). It is important to align the perspectives of various project partners for each milestone to ensure this phase's effectiveness. This can be achieved by engaging all relevant stakeholders in creating the schedule. The Master Schedule should include major project milestones and highlight deliverables to be released once the milestone is complete. It should also identify potential constraints that could impact the project timeline so that the project team can take steps to mitigate these risks. The Master Schedule should be used to monitor project progress and ensure that the project is on track to meet its deadline. It provides a high-level overview of the entire project, including major activity start and end dates and dependencies between activities, so the project team can better understand the critical path. By engaging the project team, including all relevant stakeholders, the Master Schedule ensures that everyone clearly understands the project timeline and their respective roles and responsibilities.

In the Pull Planning phase of LPS, the project team comes together to plan the work that needs to be done in the next two to four weeks, creating a detailed and accurate plan for the work to be executed. This phase is crucial for the project's success, as it enables the team to identify and resolve any issues before they become problems and complete the project on time and within budget. During the Pull Planning phase, the project team identifies the work to be performed, determines the resources required, and sequences the activities in the most efficient manner possible. The team also engages project stakeholders to ensure that everyone is on the same page and that the plan is feasible. By working together, the team can coordinate their efforts and ensure that the project is executed smoothly and efficiently. One important aspect of Pull Planning is the identification of potential bottlenecks or risks and the development of contingency plans to mitigate these risks. This is crucial for the project's success, as it helps the team anticipate and resolve problems before they occur. In addition, the team regularly reviews the work that has been completed, assesses the status of the work in progress, and identifies any changes to the work plan. This helps to ensure that the project stays on track and that the timeline is updated as necessary (Hamzeh et al. 2009). Another key aspect of Pull Planning is the engagement of the project team, including all relevant stakeholders, which ensures that everyone clearly understands their respective roles and responsibilities and that everyone is working together towards a common goal. By working together, the team can create a detailed plan for the next four weeks, including the work to be performed, the resources required, and the sequence of activities. This allows the team to coordinate their efforts and ensures that the project is executed smoothly and efficiently. Pull Planning is a critical phase in the Last Planner System. It enables the project team to identify and resolve issues, coordinate their efforts, and ensure that the project is executed smoothly and efficiently. By working together, the team can complete the project on time and within budget while ensuring that everyone is on the same page and that the project timeline is updated as necessary.

The Lookahead Planning phase is a crucial aspect of construction project management utilizing the LPS. This phase is dedicated to creating a comprehensive plan for the upcoming work period based on the current state of the project and any potential changes that may impact the schedule or scope of work. This phase aims to ensure that the project is progressing smoothly and efficiently and that the team is prepared to execute the work as planned. The process of Lookahead Planning starts with the project team meeting to review completed work, assess the status of work in progress, and identify changes to the work plan. The team then collaborates to develop a detailed plan for the next four weeks, including the work to be performed, the resources required, and the sequence of activities. This plan is crucial in ensuring that the project is executed efficiently and effectively, as it provides a roadmap for the team to follow. One of the key benefits of Lookahead Planning is its ability to anticipate and resolve problems before they occur. This proactive approach ensures that the project remains on schedule and that the team is prepared to handle any challenges. The team can identify potential bottlenecks or risks and develop contingency plans to mitigate these risks. This level of preparation and foresight is essential in construction project management, as it helps to minimize the risk of delays and ensures that the project is completed on time and within budget. To further ensure the project's success, the team reviews the plan with project stakeholders to ensure its feasibility and ensure everyone is on the same page. By involving all stakeholders in the process, the team can ensure that everyone knows the project's goals and objectives and understands the work that needs to be done. This level of transparency and collaboration is critical in ensuring that the project stays on track and that all parties are aligned in their efforts (Sheikhkhoshkar et al. 2023). Lookahead Planning provides a comprehensive plan for the following work period and ensures that the team is prepared to execute the work as planned. By anticipating and resolving problems before they occur, the project remains on schedule, and the team can coordinate their efforts efficiently. Through regular meetings and collaboration with project stakeholders, the team can ensure that the project is executed smoothly and that everyone is aligned in their efforts toward its success (Hamzeh et al. 2009).

The Weekly Work Planning (WWP) phase of the LPS in construction project management is crucial to ensure the successful execution of the project. This phase involves creating a detailed plan for the work to be performed in the upcoming week based on the Lookahead Plan and the project's current state. In the WWP, extensive collaboration is required to aid each other in executing tasks and among workers and their superintendents to obtain instructions and directions. Also, deviations from the schedule are detected, analyzed, and addressed by all participating project members, and handoffs among different trades and members are handled and finalized, necessitating continuous and thorough discussions and collaboration (Hamzeh et al. 2009; Seppänen et al. 2010). The first step in the WWP phase is a meeting between the project team to review completed work, assess the status of work in progress, and identify changes to the work plan. The team then develops a detailed plan for the work to be performed in the upcoming week, including work, resources, and activity sequence. Through these collaborative efforts, the WWP phase aims to ensure that the project is progressing efficiently and that the team is prepared to execute the work as planned. By planning the work every week, the team can coordinate their efforts, ensure that the work is performed as planned, and identify and resolve any potential issues before they become problems. Finally, the weekly work plan is reviewed with stakeholders to ensure that everyone is on the same page and that the work plan is feasible. Day-to-day collaboration on site is key, either to abide by the plan or to adjust to the plan when necessary. Through these collaborative efforts, the Weekly Work Planning phase of the Last Planner System helps to ensure the successful and efficient execution of the construction project. The discussed collaborative actions are classified into the different LPS phases and represented in Table 1 below. While Table 1 is not exhaustive, and some additional collaborative actions might occur during the LPS phases, it exhibits the main actions that require collaboration among the project members during the planning and execution phases of a construction project.

Table 1: Collaboration Actions in the LPS

Master Scheduling	Pull Planning	Lookahead Planning	Weekly Work Planning
Aligning perspectives	Understanding the scope	Reviewing completed work	Reviewing completed work
Setting major project milestones	Identifying activities	Assessing work in progress	Assessing work in progress
Identifying potential constraints	Sequencing activities	Identifying work plan change	Identifying work plan change
Providing a high-level overview	Identifying required activity resources	Developing a detailed plan for the lookahead period	Developing a weekly work plan
Engaging the project team	Allocating resources	Assigning task responsibilities	Reviewing weekly work plan
	Agreeing on planned activity dates	Reviewing the plan with project stakeholders	Analyzing constraints
	Identifying critical activities	Sharing knowledge to identify constraints	Resolving potential issues
	Designing successful handoffs	Agreeing on which risks are allocated and which risks are shared	Addressing schedule deviations
			Sharing efforts and instructions to execute tasks
			Discussing handoffs finalization

AGENT-BASED MODELLING AND SIMULATION OF COLLABORATION DURING THE LPS

In order to investigate the impacts of collaboration carried out at different phases throughout a construction project, an agent-based simulation model was built using AnyLogic v. 8.7.10. The model included two agent populations: tasks and members. Data from a sample project were used. Agent-based modeling (ABM) is a computational modeling that focuses on simulating the actions of individual agents and how they interact with one another and their environment. ABM is useful for studying multi-interacting complex systems, such as social, economic, and ecological systems.

MODEL DESCRIPTION

The task population included 14 agents representing 14 individual tasks. It was assumed that the project included five trades, so each modelled task was randomly assigned to one of the five trades. Each task agent was assigned a set of attributes, including an ID number, a trade it belongs to, a planned duration, a planned date for pull planning, a planned date for lookahead planning, a planned date for execution, and a set of predecessors. It also included a statechart, where the task agent moves from one state to another based on its progress. The statechart was divided into three main sections representing (1) pull planning, (2) lookahead planning, and (3) weekly work planning, each containing parameters that specify the required number of superintendents, the required number of workers, the required number of collaborations among superintendents, and the required number of collaborations among workers.

Conditions and functions in the model drove the behavior and progress of the task agents along the different states. The overall behavior of each task agent is described as follows: Once a task's pull planning date is due, it moves from the "not_due_yet" state to the "plan_pull" state, where it starts preparing for its pull planning phase by checking that all superintendents are idle. Once checked, the task agent sends all superintendents messages to start pull planning and moves to the "start_pull" state. Once the number of completed collaborations among the superintendents reaches the required number of collaborations, the task agent moves to the "wait_for_lookahead" state, where it waits for one week after its actual pull planning start date. It then moves to the "plan_lookahead" state, where is starts preparing for the lookahead planning phase by checking that the superintendent of the trade it belongs to and another superintendent for another trade are idle. Once checked, it moves to the "Start_Assigning" state, where it assigns several worker agents based on the prespecified required number of workers belonging to the same trade. Once the required number of workers is achieved, is moves to the "start_lookahead" phase until the number of completed collaborations among superintendents and number of completed collaborations among workers reach the required values. Afterwards, the task agent waits for one week after its actual lookahead planning start date to pass before going through the "Weekly Work Planning" phase states, which are identical to those of the "Lookahead Planning" phase, except for the values of the required numbers of workers and superintendents and the required number of collaborations among workers and superintendents, which vary based on each phase. Once the required collaborations are achieved, the task agent moves to the final "complete" state and notifies the tasks that follow it that they may start. The simulation is stopped once all 14 tasks are completed.

As for the members agent population, it included five superintendents (one for each trade) and several workers. Each member agent was given an ID, a role specifying whether they are superintendents or workers, and a trade they belong to. Each member was also given "willingness" to collaborate, "engagement" in the process, and "scope familiarity" parameter values. These parameters were used to calculate each member agent's "probability of collaboration". They were chosen based on the literature review carried out in the previous sections, proving that positive functional relationships may exist between the three factors and collaboration. The values of these three parameters vary among the different scenarios, which will guide the analysis process in this study. Finally, the probability of collaborating for each member agent is calculated as the average of the aforementioned three parameters. During each phase, if the member agent's probability to collaborate is higher than 5, they collaborate. Otherwise, they do not. In this case, they return to their phase and increase their probability to collaborate by a specified value. Member agents moves between the "Idle" state and the three states of the different phases, i.e. "pull planning", "lookahead planning", and "execution", based on messages received from the task agents to start or stop working on a specified phase.

SIMULATION SCENARIOS

Various scenarios were simulated to investigate the impact of collaboration on the different LPS phases. The scenarios were driven by the changing values of the modelled factors impacting the chance of collaboration among agents, which are each agent's "willingness" to collaborate, "familiarity" with the scope of the tasks in hand, and "engagement" in the process. The different modelled scenarios are shown in Table 2. The terms "high" and "low" refer to the modelled probability of collaboration among agents during the different phases. For example, in scenario 1, member agents were assigned low ranges of factor (willingness, engagement, and familiarity) values to decrease the probability of collaboration among all LPS phases.

Table 2: Modelled Scenarios and Their Assigned Collaboration Probabilities

Scenario	Pull planning	Lookahead	WWP
1	Low	Low	Low
2	High	Low	Low
3	Low	High	Low
4	Low	Low	High
5	High	High	High
6	Low	High	High
7	High	Low	High
8	High	High	Low
9	Average	Average	High
10	Average	Average	Low

ANALYSIS AND DISCUSSION

The model was run for various scenarios as outlined in Table 2, and the results are displayed in **Error! Reference source not found.**(a) and **Error! Reference source not found.**. These fi gures illustrate the obtained durations (in days) based on the different scenarios in the simulation model. The study variables represent the level of collaboration in the pull planning, look-ahead planning, and weekly work planning phases. For a methodical analysis of the different scenarios and results, the two extremes in the levels of collaboration are examined as a first step: high collaboration in all phases (referred to as “best” scenario) and low collaboration in all phases (referred to as “worst” scenario). Doubtlessly, the highest level of collaboration in all three phases leads to the shortest project duration (86 days), emphasizing the vital role of collaboration in each stage of the LPS, while low collaboration in all three phases leads to the longest project duration (168 days), stressing the need for collaboration throughout the entire LPS and the involvement of all stakeholders in the planning and execution process.

When collaboration is high in the pull planning and look-ahead phases but low in the weekly work planning phase, the project duration extends slightly (94 days) compared to the best scenario, highlighting the importance of collaboration in the weekly work planning phase for maintaining project momentum and ensuring that all team members are on the same page. However, this scenario generated the second shortest duration among all scenarios, implying that despite the lack of collaboration during execution, the undertaken collaboration attempts early on in the project during the planning phases guaranteed a safe degree of satisfactory duration results.

On the other hand, when comparing this 94-day result with its neighbouring and high 116-day result obtained by only decreasing the level of collaboration in the pull planning, we can deduce the significance of collaboration carried out in the early stages of the project. This result indicates that early involvement is crucial for an efficient performance and a successful construction project.

The second longest duration among all scenarios was obtained from the one with low collaboration in pull planning and lookahead planning but high collaboration in the weekly work planning (142 days). This result indicates that despite collaborative efforts being exerted during execution, the lack of early collaboration during the planning phases rendered the early project completion near impossible. To further reinforce this hypothesis, by analysing the scenario right above it, which is obtained by only increasing the collaboration level in the pull planning phase, a 103-day duration was obtained, showing a significant reduction in the duration of the project by enforcing collaboration in the early pull planning phase.

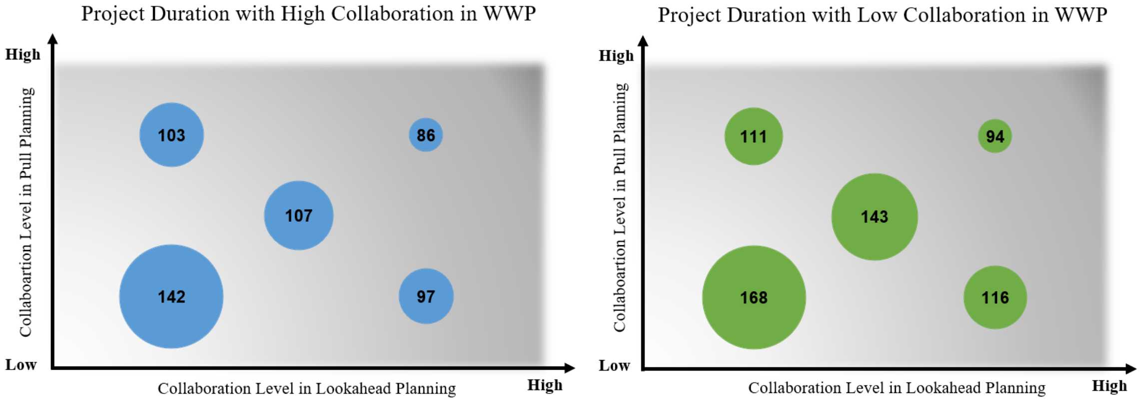

Figure 1: The project duration in case of high, average, and low collaboration in pull planning and lookahead planning with (a) high collaboration in the WWP and (b) low collaboration in the WWP

Figure shows the percent increase in project duration for different scenarios compared to the "best" scenario with high collaboration in all phases. As the level of collaboration decreases, the difference from the best result increases. For example, when collaboration is low in all three phases, the difference from the best result is 95% (168), which highlights the importance of collaboration in all phases of the LPS for a successful and efficient construction project. When collaboration is high in the pull planning and lookahead phases but low in the weekly work plan phase, the difference from the best result is only 9% (94), which further reinforces the importance of early collaboration.

The difference from the best result serves as a measure of the impact of collaboration on project duration and demonstrates that high collaboration results in shorter project durations. The difference from the best result is a useful benchmark for assessing the impact of collaboration on construction projects using the Last Planner System. It demonstrates the importance of collaboration in all phases of the LPS for a successful and efficient project outcome.

This study emphasizes the complexity of collaboration in construction, underlining the need for accurate quantification of its impact on project performance. Effective implementation of LPS relies on fostering a culture of communication and collaboration among all stakeholders involved in the construction project. LPS has been proven to be an effective way of improving workflow in construction production systems and creating a social network among subcontractors, which enhances coordination among trade crews. Thorough implementation of LPS can strengthen social networks, contributing to improved coordination among construction teams and building relationships. However, the success of LPS is dependent on the whole system's thinking and learning culture. Avoiding excessive centrality in LPS meetings is important, as this can affect the necessary distribution of connections and responsibilities. While social network metrics such as network density, average degree, diameter, and average path length are significant factors in project performance (Castillo et al. 2017, 2018; Priven and Sacks 2015a; b), the quality of communication and relationships among team members in different phases of LPS should also be considered.

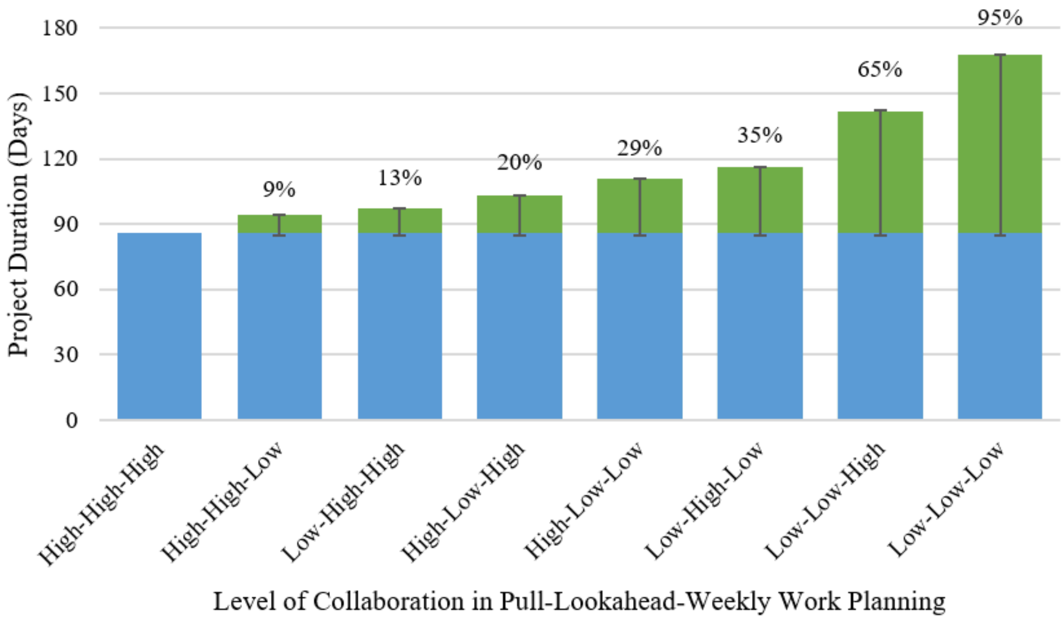

Figure 2: Percent Increase of Project Duration in Each Scenario Compared to "Best" Scenario

CONCLUSION

The findings of this study emphasize the critical role of collaboration in various phases of the LPS in ensuring successful and efficient construction projects. Clearly enough, high collaboration in all three phases of the LPS was found to result in the shortest project duration, while low collaboration in all phases resulted in the longest duration. Simulation results also highlighted the significance of early involvement of project members in the collaboration process, as scenarios with high collaboration in the planning phases resulted in short durations, while those with low collaboration in the early pull planning phase resulted in longer durations, despite having high collaboration in the later stages. The difference from the best result serves as a valuable benchmark for evaluating the impact of collaboration on project duration, emphasizing the need for prioritizing communication and cooperation among all stakeholders in the LPS.

The varying duration results prove the importance of investigating and accurately quantifying the impacts of collaboration on construction projects. They also demonstrate how changes in the levels of collaboration during the different LPS phase have different impacts on the durations, which proves that impacts of collaborative efforts vary depending on when they are being exerted. Finally, the importance of early collaboration in construction projects is clearly manifested in the conducted comparison and analysis.

The study sheds light on the complexity of collaboration in the construction and the need for precise quantification of its impacts on project performance. The study aimed to address this gap by investigating the impact of collaboration in different phases of the LPS and utilizing computer simulation to model collaboration among project members. The conclusion highlights the importance of early collaboration in construction projects and the need for further research to accurately quantify qualitative aspects of collaboration in construction.

The limitations of the study include the lack of detailed investigation into the specific factors that influence collaboration on project performance. The study does not account for individual factors that may impact collaboration, such as a member's familiarity change with the project scope and their role within the construction team. For instance, the study did not investigate the varying degrees of engagement between a superintendent and a construction worker during different phases of the project. Future research could address studying the impacts of individual factors that influence collaboration on performance.

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METHODOLOGY TO QUANTITATIVELY ASSESS COLLABORATION IN THE MAKE-READY PROCESS

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ABSTRACT

The Last Planner System (LPS) promotes collaboration to plan, prepare and execute work systematically. Make-Ready Planning (MRP) is a key LPS component, connecting mid- and short-term planning by proactively identifying and removing constraints. However, systematic deficiencies in MRP implementation have been observed, and MRP assessment mechanisms are limited to constraint management indexes and qualitative assessment of practices. Hence, finding easy to apply ways to quantitatively assess MRP collaboration and its impacts on LPS performance is identified as research opportunity. To address this, a Design Science Research approach was used to propose a methodology for evaluating MRP collaboration using Social Network Analysis (SNA) of objective LPS information captured by existing Information Technology (IT) support systems. This approach allows for the creation of a directional social network of interactions between constraint removal (source) and task execution (target) last planners. Assessing the average degree, centrality, heterogeneity, number of connected components and density allows to identify collaboration improvement opportunities as well as understanding the impact of collaboration on LPS performance, as the project progresses.

KEYWORDS

Last Planner System ®, make-ready planning, constraint analysis, collaboration

INTRODUCTION

The Last Planner System (LPS) is a highly effective production planning and control system that is based on the principles of Lean Construction (Ballard & Howell, 2003). It uses a pull framework, in which upcoming work is planned in increasing detail as required for preparation and is only pulled to execution once all potential constraints have been removed (Ballard & Tommelein, 2016). This aims to increase planning reliability through a collaborative effort to stabilize the workflow (Alarcón et al., 2014). LPS takes its name from the concept of last planners, the direct personnel in charge of preparing and executing work on site (Ballard & Howell, 2003). Last planners can be directly or indirectly responsible for task execution,

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through the identification and removal of constraints such as materials, equipment, information, labor, or conditions (Retamal et al., 2020). Instead of relying on a traditional top-down approach, last planners form cohesive horizontal networks in which execution compliance and plan reliability are facilitated by the collaborative assessment and preparation of work, in a process known as Make-Ready Planning (MRP) (Ebbs & and Pasquire, 2018).

MRP is the key link between Lookahead Planning and Short-term Planning (F. R. Hamzeh et al., 2015). The first is the process of identifying, detecting, assessing, and planning upcoming work in a three to six weeks scope, and the second consists of selecting executable work in a scope of one to two weeks, establishing commitments that will be followed throughout, and assessing compliance at the end to determine improvement opportunities (Ebbs & and Pasquire, 2018). The effective transition from Lookahead to Short-term Planning requires a sufficient workflow of executable tasks aligned with the mid-term goals (Hamzeh et al., 2015). Hence, MRP focuses on generating a Workable Backlog (WB) of constraint-free tasks, ready for commitment and execution. A larger WB allows last planners to better align commitments with their capacity, and establish more reliable commitments with flexibility to pull work in Lookahead Planning (Pérez et al., 2022).

MRP relevance is well-documented, and researchers have found a direct relationship between MRP effectiveness and long-term project performance as well as statistically significant positive correlations between the Percent of Constraints Removed (PCR) (Ballard & Tommelein, 2016), the Percent Plan Complete (PPC) and Schedule Performance Index (SPI), indicators that capture the results of the MRP, short-term and long-term planning, respectively. Nevertheless, MRP has been found to be one of the weakest implemented LPS components, significantly lower than aspects such as commitment-based short-term planning and searching for Reasons of Noncompliance (RNCs) (Daniel et al., 2015). Thus, researchers argue that implementing LPS with a short-term focus instead of a systematic mid-term planning and work preparation approach significantly limits its potential benefits (Lagos et al., 2022).

Improving MRP requires continuously assessing the effectiveness of constraint identification, committing and removal; employment of correct practices and benchmarking its results (Ballard & Tommelein, 2021). The results of MRP can already be captured using LPS indicators such as the PCR, Tasks Made Ready (TMR) and Tasks Anticipated (TA) indicators, while practices can be assessed using multiple implementation guidelines, maturity and adoption surveys (Lagos et al., 2019). However, there is a gap in the systematic assessment of last planners' collaboration to identify, manage, and remove constraints in an effective and efficient manner. Construction management requires multiple stakeholders, from suppliers to engineers and subcontractors to work in coordination under fast changing conditions (Ebbs & and Pasquire, 2018; Lagos et al., 2022). Without MRP collaboration, Last Planners can plan to execute constrained work packages or fail to detect executable packages when committing in short-term. In a high-performing LPS team, silos are replaced with closely tight networks, where Last Planners communicate actively to commit work or request its preparation (Castillo, Alarcón, & Salvatierra, 2018; Ebbs & and Pasquire, 2018)

Social Network Analysis (SNA) has been used as a diagnostic tool to assess collaboration and information flows in Lean Construction and AEC (Herrera & Alarcón, 2022). Its use in research and practice allows discovering unknown patterns of information flow and comparing them against expected interactions, also allowing to surpass preconceived perceptions of team collaboration (Priven & Sacks, 2013). SNA can be applied to multiple networks from general interaction to planning, problem-solving and learning (Alarcon et al., 2013). Also, it provides a wide array of indicators for objective representation of these networks, such as density, centrality, homogeneity, and isolated components, among others (Marin & Wellman, 2011).

SNA has mostly been applied in Lean Construction via perception surveys and required significant information preprocessing through tools to obtain representative graphs and indicators (Castillo, Alarcón, & Salvatierra, 2018). However, the AEC industry has considerably increased its technological adoption during the past decade, especially since the start of the pandemic (Assaad et al., 2022; Elrefaey et al., 2022). This has prompted the adoption of IT support systems for LPS, which can be easily use in combination with data science tools in a single stream, to facilitate the use of SNA applied to existing information being captured periodically by LPS software, instead of relying on surveys.

This research proposes a methodology to evaluate MRP collaboration and its impact on LPS performance, by applying SNA to objective LPS information captured by IT support systems for LPS. Resulting metrics from mapping interactions between constraint removal (source) and task execution (target) last planners (LPs), can complement existing LPS indicators, facilitating the identification of improvement opportunities.

RESEARCH METHODOLOGY

This research aims to propose a methodology to assess last planner collaboration on the make-ready process, based on objective information generated through mid- and short-term planning. The Design Science Research (DSR) methodology was selected as it facilitates the generation of prescriptive knowledge to model and solve complex problems. DSR focuses on designing artifacts, such as methods, models, or tools, that capture the existing understanding of the problem, its requirements, key factors, and their relationships, as well as goodness criteria necessary for potential solutions (Da Rocha et al., 2012). Thus, artifacts, can be iteratively refined by testing their fitness to model and facilitate finding solutions to the intended problem.

The following two questions were formulated to structure the research: "How can MRP collaboration be assessed using existing LPS information?" and "How can MRP collaboration metrics complement existing LPS indicators to assess performance?", consequently, the research was structured into four stages:

1. **Problem space:** Assessing the existing body of knowledge to model how MRP collaboration and its impacts LPS performance.
2. **Solution space:** How to capture MRP collaboration using existing LPS information.
3. **Artifact design:** Proposing a methodology matching the problem and solution spaces.
4. **Artifact testing:** Validation with empirical information from LPS case studies.

LITERATURE REVIEW

BODY OF KNOWLEDGE REGARDING THE PROBLEM SPACE

LPS promotes horizontal collaboration to assess, prepare and commit upcoming work, reliably, through systematic short-term cycles (Priven & Sacks, 2013). According to the supporting body of knowledge, failing to assess upcoming work will limit the team's capability to identify constraints and plan accordingly, while failing to prepare it through constraint removal will limit their capability to formulate and accomplish reliable execution commitments (Retamal et al., 2020). Previous transversal studies have observed statistically significant correlations between the PCR, PPC and SPI (Lagos et al., 2019). In despite that a full understanding of these relationships would also require connecting them to mid-term assessment and work preparation indicators, such as Tasks Anticipated (TA) and Tasks Made-Ready (TMR), these missing links have been partially covered by constraint management indicators such as the Constraint Identification Time (CIT) and Constraint Removal Efficiency (CRE) (Ballard & Tommelein, 2016; Pérez et al., 2022). CIT measures how far ahead are constraints being identified, compared to the Lookahead scope, while CRE compares the actual time needed to remove them, against the planned time committed when the constraint was identified (Lagos & Alarcón, 2021).

Both the CRE and CIT exhibited empirical correlations with the PCR and PPC (Pérez et al., 2022).

On the other hand, transversal studies using SNA to assess LPS interactions have discovered statistically significant relationships between SNA metrics of collaboration, LPS indicators and project performance measures (Castillo, Alarcón, & Salvatierra, 2018; Retamal et al., 2020). Particularly, stronger collaboration in the exchange of relevant information, as well as planning and problem solving, captured through SNA metrics of density and average degree, showed statistically positive correlations with constraint release and planning effectiveness, measured by the PCR and PPC (Castillo, Alarcón, & Salvatierra, 2018). A subsequent study by the same authors also correlated the network strength metrics with benefits in quality, safety, costs, and productivity (Castillo, Alarcón, & Pellicer, 2018). Furthermore, a case study using a similar methodology to compare two projects of similar characteristics and LPS experience, observed that the project with higher horizontal collaboration in planning and problem solving exhibited significantly better MRP practices and long-term schedule compliance, while the project with a more traditional top-down management approach exhibited work-preparation silos that allowed to obtain high PPCs but prevented them from sustaining high long-term schedule performance due to the lack of flexibility of the WB (Lagos et al., 2022).

These studies support the statement that horizontal collaboration in planning and work preparation is key to support the LPS virtuous cycle of proactive planning, committing and control, which in terms of MRP, corresponds to (1) efficient constraint identification and (2) reliable removal (Ballard & Tommelein, 2016). Horizontal collaboration facilitates that last planners take part in this process (Lagos et al., 2022), while the strength of these interactions, i.e. close collaboration between multiple parties, leads to work preparation reliability (Castillo, Alarcón, & Pellicer, 2018). Also, since the goal of MRP is to facilitate the reliable commitment and execution of upcoming tasks, MRP effectiveness can be assessed by three subsequent factors: Effective work preparation, reliable work commitment and schedule compliance (Ballard & Tommelein, 2016). Therefore, based on these relationships and supporting evidence, the problem space is modeled by a six steps process from lookahead planning to sustained schedule compliance, aided by strong horizontal last planner collaboration, as shown in Figure 1.

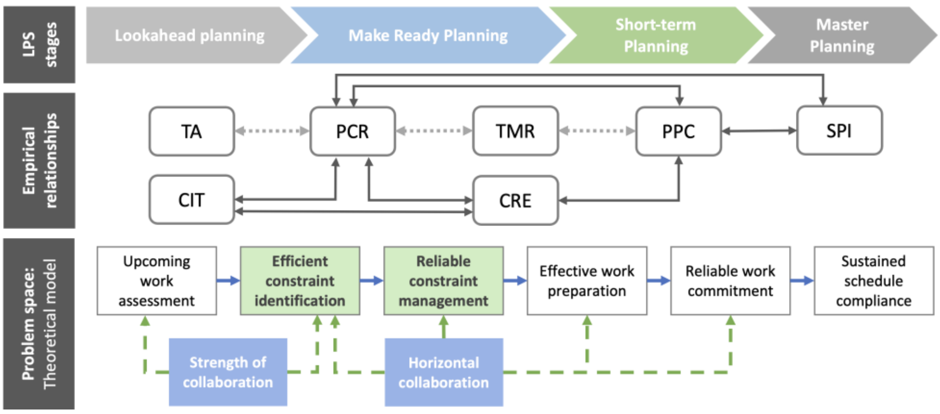

Figure 1: Theoretical Design of the Problem Space

Body of Knowledge Regarding the Solution Space

Social network analysis (SNA) studies the relationships and connections between individuals in a network, allowing to represent them in quantitative metrics as well as graphs (Marin & Wellman, 2011). It allows to study the structure and dynamics of a network, as well as the roles and influence of the different actors within it. SNA has been used in LPS to study the communication and collaboration patterns among the different stakeholders, including project managers, contractors, subcontractors, and the wider project team (Priven & Sacks, 2015). SNA facilitates identifying key roles such as connectors, bottlenecks, influencers, and decision-makers, as well as areas with lacking communication or collaboration (Flores et al., 2014).

Researchers have mainly captured social networks by employing indirect means, consisting in surveys of perceived interactions, applied to all members of the network (Herrera & Alarcón, 2022). These surveys cover general as well as specific interaction such as information exchange, planning and problem solving, learning, leadership, and feedback, among others. The surveys ask each team member a linking question, that can be (1) bidirectional, such as with "whom do you interact for this specific purpose?" Or directional, such as "who provides you key information necessary to carry out your work?" Also, responses can be binary or weighted, usually by a perceived frequency or relevance of the interaction (Alarcon et al., 2013).

Although researchers have used both bidirectional and directional links to capture networks, the later are preferred, since they allow to assess an individual's interactions based on the times it was targeted by other team members (incoming links), instead of by their own perceived interactions (outgoing links), helping to remove respondent bias (Cisterna et al., 2018; Herrera et al., 2020). Also, the way in which the question is formulated and the use of incoming or outgoing links can affect the network's representativeness. For example, if outgoing links are used to map an information exchange network, asking "to who do you provide relevant work information?" would have a higher risk of bias than asking "who provides relevant information for your work?". The use of objective information captured by IT support systems employed in LPS can help remove the risk of biased responses.

Regarding the assessment of MRP collaboration, some of the metrics used to quantify and describe the structure and dynamics of a network include the (Arif, 2015):

Density: Represents the strength of the network, as the number of existing connections over the total possible connections between its nodes. Hence, the higher the density, the higher the number of direct connections between the network's individuals.

Clustering coefficient: This measures the degree to which an individual's connections are connected to one another. It is often used as a measure of the cohesion of the network since it provides a representation of how likely is an individual to reach all others through its connections.

Closeness: Distance of an individual to all remaining nodes of the network. Equates to the number of interactions required to reach the remaining individuals. Therefore, is a measure of easiness of communication or the spread of information.

Path length: Average distance between any two individuals in a network. It is often used as a measure of the efficiency of information or resource flow through the network.

Degree: Relevance of an individual in a network via the number of connections (links) it possesses. It can be measured by the outgoing, incoming, or bidirectional links, using weighted or binary connections.

Betweenness: This measures the extent to which an individual is a "bridge" between other individuals in a network. It is often used as a measure of an individual's potential control or influence over the flow of information or collaboration within the network.

Eigenvector centrality: This measures the importance of a node in a network based on the importance of its neighbours. It is often used as a measure of how likely a node is to be reached by a random individual through its connections in the network.

Since the focus is placed in the assessment of network collaboration during MRP, individual metrics should be transformed to represent the cohesion, efficiency, and efficacy of the make-ready planning network, and not of a specific individual. Common practice is averaging individual metrics to represent the network, for example, using the average degree and average clustering coefficient as measures of cohesion. On the other hand, the following LPS metrics were selected to represent the short-term cycle's components (Hamzeh et al., 2019):

Percent Constraints Removed (PCR): Represents the constraint management reliability, measuring the number of constraints effectively removed during a short-term period, over the number of constraints planned to be removed during that cycle.

Percent Plan Complete (PPC): Represents the short-term planning reliability, measuring the number of short-term task execution commitments accomplished over the number of commitments made.

Schedule Performance Index (SPI): Represents the accomplishment of the master plan at the end of each period, by comparing the accumulated progress against the expected progress according to the initial plan, i.e., the Baseline.

SOLUTION ARTIFACT

To support LPS, IT systems require to capture and monitor commitments on a short-term basis. Therefore, they must contain four sources of information: (1) Tasks, which conform the master plan, (2) Constraints, which are linked to tasks, (3) Last Planners, who identify, plan, commit and manage tasks and constraints, and (4) terms, which contain the constraints and tasks committed in every period and their compliance. As last planners manage their short-term cycles, they will take tasks from the master-plan, pull them to the lookahead plan, assess them in search of constraints to be committed and once these are removed, the tasks are committed and executed accordingly. This process is captured periodically as terms.

The solution artifact represented in Figure 2 was developed with these four sources of information in consideration, to represent the transition from Lookahead Planning to short-term and master planning outcomes, via make-ready planning. The existing LPS indicators PCR, PPC and SPI are used to represent compliance and variability of performance in make-ready, short-term and master planning, respectively. In addition, a PWC indicates the Percent of Work Complete (PWC) indicator, explained in detail in the following sections. Finally, the relationship between constraint identification, reliable removal, the strength and horizontalness of collaboration is expanded using a set of SNA metrics taken from the existing body of knowledge and the aforementioned LPS indicators.

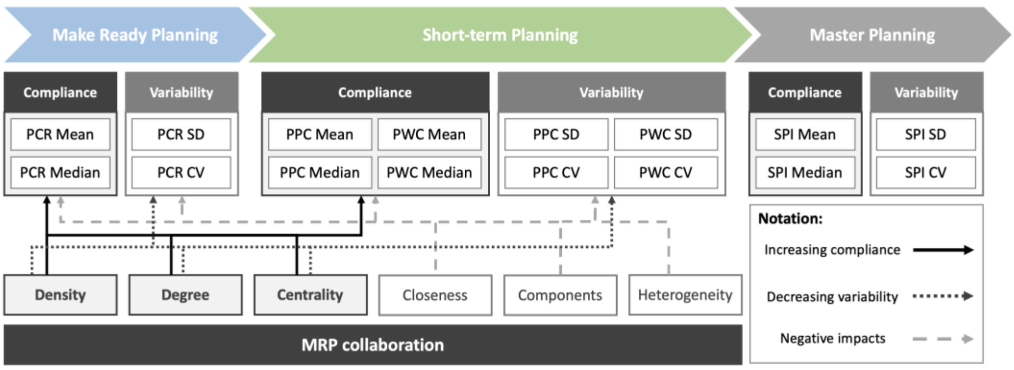

Figure 2: Solution artifact design

MRP NETWORK

Since MRP focuses on committing constraint removal to prepare the work, the MRP collaboration network can be mapped using the relationships between constraint Last Planners, the tasks' constraints, and the tasks' Last Planners. The MRP represents directional relationships, where the Last Planners committing the constraint removal, or Indirect Last Planners (ILP) prepare the work of the Last Planners that subsequently commit the execution of the task being prepared, i.e., the Direct Last Planners (DLP). Hence, MRP forms directional networks linking an ILP to a DLP. The indirect last planner acts as a source node, who removes constraints for the direct last planner, i.e., the target node. An ILP who prepares more work for a given DLP would have a higher relevance, giving way to a directional weighted network.

These interactions were obtained from the empirical data captured in the terms, by listing the last planners in a symmetrical two-dimensional matrix, with one dimension representing their role as DLPs and the second as ILPs. Each interaction is represented by the number of constraints which an ILP commits to remove for a DLP and the number of tasks that the DLP has committed. The ratio between the number of ILP's constraints over the DLP's tasks serves as a weighting factor. The connectivity of an individual node is given by the strength of the MRP collaboration, hence, its captured by the sum of incoming weights to a node, indicating that more constraints are being removed to prepare its tasks. Since the main characteristics of interest of the network are its strength and horizontalness the following indicators were calculated from the matrix:

Degree: Strength metric obtained as the arithmetic mean of all individuals' degrees, where each degree corresponds to the sum of incoming weight.

Density: Strength metric obtained as the number of directed links observed, divided by the total potential links between individuals, where a density of 1 indicates that every individual prepares work for each of the remaining nodes.

Connected components: Inverse strength metric representing the number of disconnected sub-groups in the network. The presence of two or more components indicates that one or more individuals are disconnected from the remaining group.

Heterogeneity: Inverse homogeneity metric representing the coefficient of variation of the mean degree, calculated as the standard deviation over mean. A higher coefficient of variation indicates disparity among individuals.

Closeness: Calculated as the arithmetic mean of the closeness centrality, which represents the average distance from anode to all other nodes, i.e., the average number of interactions required to reach any individual.

Centrality: Obtained as the arithmetic mean of the nodes' Eigenvector Centrality. Eigenvector centrality compares the degree of the nodes directly accessible by an individual, against the degrees of the network, where greater centrality indicates that an individual is closely connected to relevant ones.

LPS METRICS

In addition to obtaining the PCR and PPC as the percent of accomplished commitments in each term, for constraint removal and task execution, respectively, the authors also calculated the actual progress, SPI and Percent Work Complete (PWC) for each term. The SPI compares actual accumulated progress and expected progress; therefore, a baseline progress was calculated using the planned task dates at the start of the masterplan. Each task was assigned a weight equivalent to its planned execution days over the total planned execution days from all tasks in the initial plan. Each task would provide progress according to its weight distributed linearly across its execution days. The progress added by all tasks being executed was summed for each term, and the accumulated progress at the end of each term was calculated to obtain the Baseline expected progress (BL). The progress of each task was calculated at the end of each term, multiplied by the task's weight, and summed to obtain the actual accumulated progress (AP) at the end of each term. Then, the SPI divided the AP by the BL in each term.

The PWC represents the ratio between the percent of work completed in each period and the percent of work committed, using the progress, commitment, and weight of the tasks in each term. The numerator of the PWC corresponds to the weighted sum of the relative progress achieved by the tasks of a term, and the denominator, to the weighted sum of the relative progress committed for these tasks. Hence, as Equation 1 shows, the relative progress of a task is the difference between the progress achieved at the end of the current term, minus the progress achieved at the end of the previous. On the other hand, the relative commitment corresponds to the commitment in the current term, minus the progress achieved in the previous. The relative progress of each task participating in the term is multiplied by its weight and summed to obtain the relative progress of the term, and the same is done to obtain the relative commitment for that term. Then, their division represents the ratio between the actual progress gained in a term, and the progress expected by the commitments made.

$$PWC_{term\ j} = \frac{\sum_{task\ i}^{N} \left\{ \left(Progress_{i,j} - Progress_{i,j-1} \right) \cdot Weight_i \right\}}{\sum_{task\ i}^{N} \left\{ \left(Commitment_{i,j} - Progress_{i,j-1} \right) \cdot Weight_i \right\}}$$

The PCR, PPC, PWC and SPI of each term are aggregated for each project, using their descriptive statistics of mean, median, standard deviation (SD), and coefficient of variation (CV). The mean and median are used as measures of performance compliance, and the standard deviation and coefficient of variation, used to represent variability across terms.

RESULTS AND DISCUSSION

ARTIFACT TESTING METHODOLOGY

The proposed methodology was tested using empirical information from 68 projects that employed the same IT support system for LPS. All had implemented LPS for at least 8 weeks prior to the data collection and were followed for at least 10 weeks, capturing, in average 50% of their execution scope. Table 1 presents the sample's descriptive statistics. The solution artifact was validated by (1) its fitness to capture relevant relationships between indicators, as well as (2) the usefulness of MRP indicators to discover impacts in LPS metrics.

Table 1: Sample's Descriptive Statistics

Statistic	Tasks	Duration (days)	Captured scope	Terms	Constraints	Constraints per task	DLPs	ILPs
Mean	1104	494	50%	32,5	148	0,3	12,7	10,9
Median	585	494	41%	25,0	86	0,2	11,0	9,5
SD	1146	255	29%	20,3	172	0,4	8,7	5,5

The fitness was assessed with statistical correlation analyses, using the Spearman Correlation test with the raw variables and the Pearson Correlation test with the normalized variables. Normalization was performed using the standard conversion and outliers with absolute $z > 3.0$ were removed. A correlation was deemed statistically significant if the resulting p-value was lower than 0.05 and categorized as weak with $R \geq 0.3$, moderate if $R \geq 0.5$ and strong if $R \geq 0.75$.

The usefulness was assessed using statistical mean difference analyses. Each the median of each MRP metric was used to divide the universe into two samples. Then, the samples were compared in each LPS variable. The normality of both samples was assessed, and the t-test was used to compare normal distributing samples, while the Mann Whitney's U test was used if any sample was not parametric. Both tests required a $p\text{-value} < 0.05$ to detect a statistically significant difference and the process was repeated using the 6 MRP metrics to assess differences in the 12 LPS indicators.

VALIDATION RESULTS

Figure 3 maps the relationships found between the SNA and LPS metrics. As observed, MRP collaboration is directly correlated to master plan and MRP performance metrics. Also, its impact is visible through the existing correlations between the complementary LPS metrics. Out of the 58 significant correlations found, 47 were weak, 6 were moderate and 5 strong, nevertheless, all correlations presented a statistical p-value<0.05. It must also be noted that the moderate and strong correlations were found only between PPC and PWC indicators. Table 2 presents the differences in LPS indicators (Tested KPIs) detected when splitting the sample using each the SNA indicators (Sampling KPIs). Each sampling KPI was used to divide projects into groups above and below the median, and then, the groups were tested to find statistically significant differences in their LPS indicators. The table shows the 17 statistically significant differences (23.6%) found, covering all LPS indicators, except the PWC Mean and the SPI.

Table 2: Statistically Significant Mean Differences

Sampling KPI	Tested KPI	Top group	Bottom group	Difference	p-value
Density	PCR Mean	66.1%	74.9%	-11.7%	0.037
Density	PCR Median	65.7%	78.9%	-16.8%	0.020
Degree	PPC Median	69.0%	77.1%	-10.5%	0.046
Centrality	PPC Mean	67.8%	74.9%	-9.4%	0.039
Centrality	PPC Median	68.7%	77.4%	-11.2%	0.032
Centrality	PPC STD	19.4%	16.4%	18.4%	0.028
Centrality	PPC CV	31.0%	22.9%	35.0%	0.004
Centrality	PCR Mean	64.8%	76.2%	-15.0%	0.006
Centrality	PCR Median	65.0%	79.6%	-18.4%	0.012
Centrality	PCR STD	25.8%	21.3%	21.0%	0.020
Centrality	PCR CV	42.6%	30.3%	40.6%	0.007
Centrality	PWC Median	82.8%	90.0%	-8.1%	0.044
Centrality	PWC STD	27.6%	21.2%	30.1%	0.014
Centrality	PWC CV	36.8%	25.3%	45.4%	0.003
Closeness	PCR Mean	65.6%	76.0%	-13.6%	0.013
Closeness	PCR Median	64.8%	80.7%	-19.7%	0.005
Components	PCR STD	27.0%	22.6%	19.2%	0.038

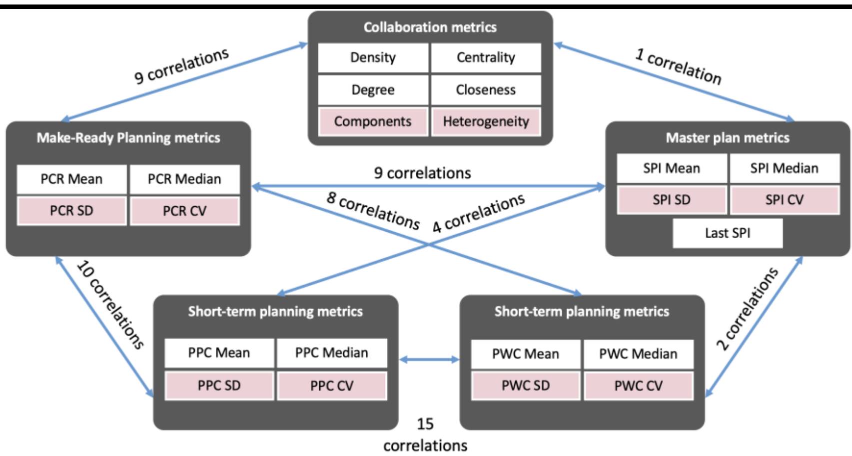

Figure 3: Correlations found Between MRP Collaboration and LPS Components

DISCUSSION

First, the results indicate that the methodology can detect relevant relationships between the 18 combined LPS and MRP indicators, as well as discovering potential impacts of MRP collaboration on LPS performance; thus, the artifact is deemed valid and provides answers to both research questions. Although most correlations found were weak, it must be noted that these were tested in a relatively small universe of case studies (68) and that the case studies presented significant variance regarding the number of tasks, constraints, DLPs, ILPs and, particularly, the number of terms registered, with half of the sample capturing between 15% and 41% of their scope. Nevertheless, the observed connectivity across all five LPS components, including the MRP collaboration poses a relevant opportunity for research that can lead to the discovery of key insights. This opportunity is also supported by the significant differences observed in LPS metrics obtained through the statistical sample comparisons.

On the other hand, it must be noted that all 17 statistically significant differences showed lower LPS indicators in the upper half of the MRP samples. These translate a potentially negative relationship between MRP collaboration indicators and LPS metrics, which must not be mistaken as a negative effect. For example, a greater number of components indicates a weakly connected network, thus, the decrease in compliance and increased variability observed are consistent with expectations. The same applies to the Closeness indicator, as a greater number indicates the necessity to go through more interactions to reach an average node. On the contrary, the network strength metrics degree and density showed relationships opposite to the expected. Authors assumed that higher density and degree would correlate to higher LPS indicators of compliance and lower variability, which was not the case. Two possible causes were inferred and should be addressed with subsequent research: The first, is that larger networks tend to be less connected. Thus, teams with less Last Planner involvement would reflect in higher network strength metrics, explaining the negative relation found between density, degree and the LPS indicators. The second is that, since the networks are weighted on the constraints to tasks ratio, a stronger network can indicate more constraints, leading to a more complex MRP process and difficulty to accomplish commitments. Finally, given that the results signal the need to further research the topic, the authors propose the continuation of this study, employing a larger sample with empirical schedule outcome indicators.

CONCLUSSIONS

This article proposed a methodology to quantitatively assess collaboration in the Make-Ready Planning process and its impacts on LPS performance, to help tackle the systematic deficiencies in MRP implementation, signalled as a gap by researchers. The authors used the DSR approach to match the current understanding of the problem with existing opportunities and designed an artifact capable of leveraging existing LPS information captured by IT support. The solution artifact employs six SNA indicators to assess MRP collaboration and complements with 12 LPS indicators to assess impacts on performance. Although the results showed mostly weak correlations between the LPS and SNA metrics used to capture MRP collaboration, the statistical differences analyses showed that when dividing projects using the SNA metrics, differences from 10% and up to 40% were found in their LPS metrics. These results allowed to validate the fitness of the methodology to identify key relationships among LPS components, captured in multiple indicators, as well as finding evidence of the impacts of MRP collaboration on LPS performance. Finally, the author acknowledge that the research should be expanded using a larger project sample with empirical schedule outcome indicators to assess its potential contributions to the state of art and practice in modelling and explaining LPS impacts on performance and the key role of MRP collaboration.

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PERSPECTIVES ON ROLES AND RESPONSIBILITIES OF PROJECT TEAM MEMBERS TO ENABLE COLLABORATIVE DECISION-MAKING PROCESS

Randi Christensen[1], Paz Arroyo[2], and Annett Schöttle[3]

ABSTRACT

The owners, architects, engineers, and contractors (OAEC) industry needs to enable a collaborative decision-making process to include different perspectives and thereby find the best solutions regarding some of the challenges we face, e.g., environmental impacts, social responsibilities, and economic pressure. Decision-making is a key element through which innovation and changes can be introduced to construction projects. The need for a collaborative decision-making process and the methods used to make decisions have been discussed in previous research. However, changing the way we make decisions calls for a new definition of the roles and responsibilities of the involved parties. In this paper, we analyze three different cases to identify the concerns of the different stakeholders and recommend how roles and responsibilities could be defined with the aim of making more collaborative, transparent, and value-adding decisions in the OAEC industry.

KEYWORDS

Collaborative decisions, choosing by advantages, roles, responsibilities, sustainability.

INTRODUCTION

This paper explores the need to change the way project team members make decisions in the owners, architects, engineers, and contractors (OAEC) industry to solve the challenges it faces, such as reducing environmental impact and improving performance. According to the World Green Building Council (2019), the construction industry is responsible for almost 40% of CO_2 emissions, and as explained by Flyvbjerg and Gardner (2023), megaprojects go over both budget and time again and again. One of the key elements to allowing for more innovation and improvements is to support more cross-disciplinary collaboration (Christensen, 2022). An idea is often born outside of the field of implementation. Therefore, to allow this cross-fertilization to happen, different disciplines or functions on the projects should meet, discuss, and agree on a way forward. However, the construction industry has a reputation for being somewhat conservative (Renz & Zafra Solas, 2016), and with the rapid changes to the constraints and context of the projects in the OAEC industry, this could work against the flexibility and change needed. Traditional organizational structures of the industry, and thereby the roles and

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responsibilities, do not allow for such flexibility and innovation, as many projects do not have a formal collaborative decision-making process, and others follow a hierarchical process (e.g., Schöttle, 2022; Whelton et al., 2001). More critical thinking is needed to question the choices we make and how we are organized to make them. It is necessary to shift from decision-making as a discrete event made by a single person in authority to a collaborative process that aligns different perspectives of a decision (Garvin & Roberto, 2013). Challenging a unique perspective better enables the recognition of the biases of others in a decision-making process (Kahneman et al., 2013). Decision-making is therefore a key element through which innovation and changes can be introduced in construction projects. Here, the authors argue for the need for more critical thinking to be introduced in projects through a well-designed process to avoid personal conflicts and biases.

With the introduction of lean construction, practitioners realized that the delivery system must shift towards a more collaborative system (e.g., integrated project delivery [IPD]). The implementation of lean methods also includes methods for decision-making, such as choosing by advantages (CBA), where teams can make decisions in a collaborative way and find innovative solutions. Tillman et al. (2012) show that IPD enables a collaborative environment in which value can be co-created, allowing for customer expectations and supplier assumptions to be challenged. Meanwhile, it has been shown that CBA is a system that allows for more innovative ideas and solutions to be integrated into the design and project execution (Christensen, 2022), potentially generating a social process in which debate, argumentation, and rhetoric play an important role in the final resolution (Martinez et al., 2016). Additionally, CBA enriches the decision-making process and cultivates a shared understanding among project team members, even when they have conflicting values, allowing for all perspectives to be included (Parrish & Tommelein, 2009). When compared with other traditional methods, CBA allows for reaching a consensus faster and with less frustration for the team (Arroyo et al., 2016). It can also foster psychological safety and inclusiveness within the project team to overcome group thinking (Schöttle et al., 2019). As such, CBA has the potential for allowing project teams to collaborate and find innovative ways to address the challenges faced by the OAEC industry. However, implementing CBA as a new lean tool can meet resistance from the project team, and there is a need to explore team members' perspectives to engage in such a collaborative decision-making process.

Without clarity on the roles and responsibilities in both preparation and governance, the introduction of new decision-making methods might lead to confusion and frustration as hierarchies and power balances shift to make room for collaboration. According to Schöttle et al. (2018), a decision-making process should consider: (1) a decision method, (2) the structure of the process, (3) governance, and (4) documentation of the decision. In the related literature, the focus has mainly been on the process of reaching a decision using different decision-making methods, while less attention has been given to participants' roles and responsibilities in relation to these methods. Some papers that look at the roles in the decision-making process are specific to a case study considering one decision on a project (e.g., Martinez et al., 2016, look at formwork system selection, and Parrish and Tommelein, 2009, discuss structural system selection). Few papers document the roles and responsibilities of multiple decisions (e.g., Arroyo and Long, 2018, who consider interiors, mechanical systems, and landscape decisions of an IT campus, and Kpamma et al., 2017, who explore participatory design).

Therefore, in this paper we focus on an initial study to assess the key elements of the roles and responsibilities in collaborative decision-making in the OAEC industry. The aim of this research is to enable better and more collaborative and transparent decision-making processes, which could allow for the integration of innovation into the projects. The study focuses on the key roles of the client, the engineers/architects, and the general contractor. The investigation is based on three cases in which we analyze the concerns of different stakeholders regarding engaging in a collaborative decision-making process before drawing preliminary recommendations.

RESEARCH METHOD

This paper aims to answer the following research questions: (1) what are the concerns of the different stakeholders regarding implementing a collaborative decision-making process on projects, and (2) how do these concerns translate into recommendations for roles and responsibilities in a project to enable a collaborative decision-making process? The nature of these questions is best aligned with a case study methodology (Yin, 2014). To answer these questions, the authors conducted three case studies in which they had direct access to the project team and acted as either internal or external consultants, therefore using an action-research approach (Dickens & Watkins, 1999; O'Brien, 1998). The three cases cover a variety of construction markets and regions: a hospital project in Connecticut, the main station in Munich, and a port in Denmark. The sources of evidence used were (1) direct observation, since some of the authors were coaching the owner or design team to implement a collaborative decision-making process, (2) project documentation based on public media, meeting minutes, surveys, and A3 reports, (3) interviews with project team members, and (4) in one case, a lessons learned workshop. The data collection details of each case study are further specified in each of the following sections.

CASE STUDY 1: CHILDREN'S HOSPITAL

This case study presents the interaction between stakeholders for a children's hospital project in the United States. The following sections present the background, data collection, and key takeaways from different stakeholders' perspectives.

BACKGROUND

The project is an urban addition of an eight-story, 185,000-square-foot children's hospital in the United States. The project duration is expected to be approximately three years, and it is scheduled to open in mid-2025. The team is set up as an IPD-lite, where the owner is a private entity with strong incentives to finish the project on time and on budget to serve a growing community. Although the owner decided not to pursue any environmental certification, they are interested in evaluating decisions and considering improvements with regards to sustainability. The project team is currently in the design phase and is composed of the owner, owner's representative, architects, general contractor, and a dedicated lean consultant.

CASE STUDY PROTOCOL AND DATA COLLECTION

The following protocol was followed to learn about the roles and responsibilities of different stakeholders and their decision-making process. (1) The researcher met with the general contractor to understand the project background and current decision-making process. (2) A presentation was held in which the CBA system was explained to the entire project team, including the owner representative, architect, general contractor, and lean consultant. Both a recording and a transcript of the meeting were shared among the stakeholders. (3) The researcher met with the design manager, who led the internal decisions for the team. The researcher gave coaching and feedback on the first two decisions using CBA. The team documented these decisions using decision-making software that all stakeholders have access to and created A3 reports that can easily be shared with the owner and other stakeholders. (4) An interview with the design manager was conducted to evaluate the project's decision making process and provide feedback.

TEAM RESULTS

The researcher was able to document the stakeholders' reactions when reading the transcripts of the presentation regarding how to set up a collaborative decision-making process. In the presentation, the researcher covered (1) why CBA is a useful method for managing decisions; (2) a description of CBA basics, including principles, vocabulary, and methods; (3) a simple but practical example; (4) several case studies that were applicable to the project team; and (5) a guided discussion on the next steps for the team. There were several key takeaways from the discussions:

- The project manager from the general contractor was pleased to be able to explore alternatives and price them in parallel, as opposed to having to wait. He pointed out that they can change their previous strategy (wait for the pre-construction estimator to price some options, and then start the discussion on whether it makes sense to go for an alternative that was more expensive than the lowest priced one). After learning about CBA, they understood they could evaluate the alternatives simultaneously and therefore potentially cut the decision time in half.
- The architects were concerned with the time needed to implement the process and who would be responsible for creating the documentation and developing the A3 reports. One of the architects asked for proof that this method saves time and money on real projects, and the researcher presented a case study (Arroyo & Long, 2018).
- The project manager from the general contractor also pointed out the need for external support from both the CBA expert and the lean consultant to help facilitate this decision-making process, stating that "many people will feel uncomfortable leading a CBA decision with their cluster."
- The project superintendent seconded that idea, stating that the team must build their own success stories rather than simply learn about others' success stories and attempt to replicate them. He also proposed that each cluster identifies one or two decisions to be made as a team.
- The owner's representative was supportive of implementing the CBA method in the clusters.

After the discussion, the researcher met with the design integration manager of the project and helped guide the implementation of CBA for selecting the type of anchoring for footings and the pharmacy trailer location. At the time of writing, the team is still working on creating a more collaborative approach to making decisions. They defaulted to the design manager to oversee all decisions instead of having each cluster lead their decisions.

CASE STUDY 2: MUNICH MAIN STATION

This case study presents an owner's strategic decision to change the project delivery system from design-bid-build (DBB) to IPD by using CBA to develop the argumentation to obtain approval from the management board of the company.

BACKGROUND

Part of the expansion of the city train service involves the reconstruction of the main station. This megaproject includes the demolition of existing buildings and constructing new buildings and a new tunnel. The anticipated cost is estimated to be €1.2 billion. The owner's project team, Deutsche Bahn Netz AG (DB Netz AG), is organized in a matrix structure. Currently, the project delivery system remains DBB, with some early contractor involvement.

CASE STUDY PROTOCOL AND DATA COLLECTION

Action research was used to collect data, with the researcher facilitating a series of workshops. In this case study, the protocol was as follows. (1) The researcher briefly explained CBA to the project lead. (2) The researcher met with the project lead and two cross-divisional leads to explain the procedure. (3) The team agreed to apply CBA for a strategic project decision (question 1: whether the project should be delivered with DBB or IPD, and question 2: if IPD was chosen, what the scope of the IPD [multiparty agreement] would be). (4) A series of five workshops were held over a period of two months (October–December) to address both questions. The workshop series started with introducing CBA via a presentation and brief examples. Different participants were involved in the workshops, based on their expert knowledge and availability. Table 1 presents an overview of the participants, including the researcher (A), different team leaders of a subproject/cross-division (B, C, D, G, H, I), one expert (E), and the project leads (F and J). The decisions were made using paper and post-its and documented via photos and an Excel spreadsheet. (5) Information on the final decision was collected in January to start the approval process. The consultant was not part of this meeting. (6) In February, the researcher interviewed both responsible project leads regarding their experience, as they had little to no involvement in the workshops. (7) In April, a survey evaluating the decision-making process was administered to all eight participants, and data were collected.

Table 1: Research Protocol

	Date & Duration	Participants	Content
Working on Q1	10/06/2022 3.0 hours	5 (A, B, C, D, E)	• Short introduction to CBA • Defining the decision steps based on questions • Defining factors, criteria, attributes, and advantages
	10/12/2022 9.5 hours	8 (A, B, C, D, E, F, G, H)	• Building knowledge regarding CBA & IPD • Adjusting factors and criteria • Defining attributes and advantages • Identifying the Paramount Advantage (PA), sequencing the highest advantages
	11/14/2022 3.0 hours	6 (A, B, C, D, E, H)	• Defining the importance of advantages • Writing down the argumentation • Defining the alternatives of Q2
Working on Q2	11/28/2022 2.0 hours	5 (A, B, C, H, I)	• Defining factors, criteria, and attributes for Q2
	12/05/2022 2.0 hours	3 (A, B, C, I)	• Determining the advantages • Defining the importance
	01/26/2023 1.0 hour	5 (B, C, D, F, J)	• Making the final call to start the approval process

TEAM RESULTS

As the researcher learned the current state of the owner's project organization, she could observe two major pain points reported by the project leads: the project managers and project engineers are afraid to make decisions, and doing so takes too long. These could be due to prior experience or the lack of a defined decision-making process. As the owner wants to change the delivery system from DBB to IPD, the decision-making process must be adapted to suit the collaborative approach and thereby enable the project engineers and project managers to take responsibility in making decisions.

After deciding on an alternative through the workshops, the team prepared an easily understandable presentation to start the approval process. The data from the interview with the project leads and from the survey indicated that, due to the transparent process and the common understanding the team created by going through the CBA Tabular method and considering different perspectives, the team felt confident enough to proceed with the argumentation to obtain approval and implement the decision.

Differentiating between DBB and IPD, the importance of having a faster decision-making process (which the team sees in IPD) was scored as 80 on a scale of 0–100. The consensus was, "The faster decisions are made, the better." Even though more people need to be integrated in the decision, the owner's project team understands that having a shared understanding created through the discussion of different perspectives will result in a stable outcome, as "everybody [will have] had a [say]" (J). This is essential, since excessive deliberations will delay decision-making and risk the project not being delivered on time. Furthermore, one survey participant pointed out that having a collaborative decision-making process helps everyone better understand the reasons for the decision, which is necessary for proper implementation. Another participant (G) replied that "conflicts or difficulties are identified and resolved at an early stage" by having an interdisciplinary team working together in a decision-making process. In addition to this data collection, the researcher facilitated production planning workshops with the owner's team. The operating division (Station & Service) also participated in these workshops, and the owner's project team experienced the value of having different perspectives working together on a plan.

CASE STUDY 3: PORT OF AALBORG

This case study presents the lessons learned from an extension of a port in Denmark. In this case, the owner had a strong focus on sustainability and therefore initiated a lessons learned workshop to bring experiences on making sustainable choices forward to subsequent projects.

BACKGROUND

The 20,000 m^2 expansion of one terminal's quay is one of two test projects after the Port of Aalborg signed up for the standard ISO-14001 Environmental Management Systems (Dagens Byggeri, 2022). After realizing that Scopes 1 and 2 (operation emissions controlled by the port) only accounted for 4% of their total CO_2 emissions, they started focusing on reducing Scope 3, which includes the CO_2 emissions from the supply chain (e.g., building materials and construction processes). In this case, it was decided to use a partnering contract with the main partners (the engineer and the contractor) and use open-book accounting. The client had separate contracts with the main contractor and the engineers, and the partners were selected based on organization and collaboration (50%), personal references (30%), and overheads (20%). The CBA methods were not applied, but several important decisions were made collaboratively to make the project as sustainable as possible. The project resulted in a 40% reduction of CO2 emissions compared to a reference design (Dagens Byggeri, 2022) and a quay that was 40% stronger than prescribed, and the project was delivered on time and within budget (Molio, 2023).

CASE STUDY PROTOCOL AND DATA COLLECTION

The client initiated a lessons learned workshop to identify key takeaways from this successfully delivered project to bring forward to subsequent projects. One of the researchers was engaged as an external facilitator for a lessons learned workshop following project delivery, using the following protocol. (1) The researcher met with one of the partners to discuss the scope of the workshop. (2) A survey was sent to the main team members (three from each of the three project partners) to collect individual insights (with a 100% response rate). (3) Analyzed data were used as the basis for planning the lessons learned workshop. (4) The researcher led a full-day lessons learned workshop with the same people who responded to the surveys, in which budget, schedule, stakeholder management, collaboration, conflict management, and risk were discussed. 5) Key takeaways from the workshop were documented, which resulted in an A3 report that contained actions for each partner and was commented on by the participants. Furthermore, this case was built on available articles from public media (e.g., Dagens Byggeri, 2022), and a presentation made at Circular Build Forum 2023 (Molio, 2023).

TEAM RESULTS

In Dagens Byggeri (2022), Brian Dalby Rasmusen, Chief of Engineering, Port of Aalborg, noted: “The project became much more sustainable than we dared to hope for.” The lessons learned workshop was initiated to identify key learnings as to why the project had been a success and what could be further improved.

Five out of nine responded in the survey that trust and collaboration were the main reasons for the success of this project. At the same time, six out of nine wrote that they were at unease with the contract and the risks owned by the client and pointed to the need for a more reliant contract in subsequent projects. Respondent 9 (client) stated that “We ended the project well, but for [the] next project we need a stronger contract to support the collaboration in case a conflict arises.” Respondent 3 (engineer) suggested that “[the contract] needs to be made more bulletproof, so the client does not own the same economic risk.” Therefore, it was concluded that in future, the client will require a decision log in which all partners anticipate future decisions, including risks related to the decisions and ownership of the risks. The engineers should be those responsible for planning the decisions. The contractor stated that they found it relevant that they managed the risk and budget but were also aware that this was a huge responsibility when working with open books, and it required clear roles and responsibilities (Respondent 2).

Another barrier was convincing suppliers that more sustainable solutions were valued. The suppliers automatically offered the alternatives with the lowest cost, despite a clear message that the project was focused on sustainability. They simply did not believe that cost was not the main constraint (Dagens Byggeri, 2022).

CROSS-CASE ANALYSIS

All three cases have different decision-making approaches, and in each case, the approach taken is a key element in the outcome of the project. In Case 1, the team started the discussion on roles and responsibilities to implement a more collaborative approach to making decisions, rather than simply asking the general contractor to focus on pricing alternatives and then asking the owner to make decisions. Even with the right stakeholders early in the project and an IPD-lite structure, most of the stakeholders did not know about CBA and needed support to implement it. They expressed the desire that every cluster presents a decision to the owner; however, in practice, this was delegated to the design integration manager of the project. Although training on CBA and support for people in leading roles is an investment of time and resources, it is essential to achieving collaboration in decision-making. Those who have the knowledge are not necessarily the same as those who have the authority to make decisions. The team needs architects/engineers who are willing to make decisions and cluster members willing to share their perspectives to evaluate the advantages of each alternative—the owner can then take that input into consideration in making the final decision. Finally, someone on the team must document the decisions (which in this case was the general contractor).

In Case 2, the project has a traditional delivery system and traditional contracts, and the team experienced the limits of transparency and collaboration that come with this traditional system. Furthermore, in this system, responsibilities cannot be transferred to the person/group of people who are best able to make decisions. Roles are defined in a hierarchical way such that the team loses too much time in making decisions-making it difficult to stay on schedule and handle unforeseen situations that arise in any project (especially megaprojects). With this realization, the owner's project team made the decision based on CBA to change the delivery system to IPD, resulting in a clear structure of the decision-making process.

In Case 3, all the survey participants indicated that they were satisfied or extremely satisfied with the collaboration of the project and the outcome. In the survey responses and in the workshop discussions, it became clear that they were somewhat relieved and/or surprised that no major misunderstandings or conflicts had occurred. As one of the participants responded in the survey: "Exciting collaboration with great potential if we can just bottle it up [and bring it with us to the next project]." With the strong focus on collaboration, the roles and responsibilities shifted from what they were used to. They ultimately decided to focus on defining roles and responsibilities at the beginning of subsequent projects. As part of the actions agreed upon in the workshop, it was stated that for future projects, stricter risk management should be put in place to support better and more transparent decision-making. Furthermore, the client stated that the future would require a more systematic approach to decision-making, where benefits, risks, and financial consequences were more clearly stated and presented in a timely manner such that a final decision could be made.

In Table 2, the concerns of each stakeholder in each case are summarized and commonalities among the cases are highlighted. By focusing on concerns, we can identify where the focus should be directed to enable more efficient and transparent decision-making processes in the future.

DISCUSSION

In general, for all the stakeholders, we have seen that to move from traditional to recommended practices, an IPD (or IPD-like) contract is not enough to break the barriers for collaborative decision making. Collaborative behaviors need to be reinforced, and the team must be intentional and deliberate in creating new roles and responsibilities that allow for new ideas and concepts to be incorporated. In short, it all starts with the owner and the user. The owner must define and communicate their vision to provide direction regarding the project strategy and the embedded decisions. This means the owner must be involved in the decision making process early on (not only at the end by questioning the recommendations). For example, in Case 2, the owner realized that there is a gap in taking responsibility by project team members within their own organization, which in turn leads to slow decision making. By understanding the importance of roles and responsibilities, the team can work on the definition earlier in the project, and roles and responsibilities can change in long-term projects as new team members and partners join the project.

Table 2: Concerns of the different stakeholders that influence the decision-making process

	Case 1:	Case 2	Case 3
Owner	Finish on time and within budget. Obtain the right value for patients. Set up an effective decision-making process.	Finish on time. Have a stable schedule. Some are afraid of making decisions. Concerns over decision-making taking too long.	Integrate sustainability into the project as far as possible. Some concerns over the risk related to economy and quality.
Architects/ Engineers	Provide design solutions on time. Manage documentation. Decrease the time spent on meetings and decision-making.	NA	Concern for the client, as the client owned all the risk.
General Contractors	Manage team clusters efficiently. Provide budget and make decisions in a timely manner.	NA	Manage the budget on behalf of the team. Felt responsible for the trust shown by the client. Concerns over receiving the right input from suppliers.

In the three cases, we see the owners moving away from being focused primarily on cost and time, to focusing more on value creation within constraints and understanding cost and time as an output of collaboration. In Case 3, we saw that it was difficult for the rest of the supply chain to understand that the main constraint was not time or cost, but sustainability. In comparison, in Cases 1 and 2, the owner understands that the project's goal of finishing on time needs the integration of different stakeholders to find the best solutions by creating a common understanding of project needs. Therefore, the owner has a great responsibility in guiding the rest of the team to focus on values rather than only focusing on schedule and cost. If the focus is on sustainability or creating the best project for users, this should be communicated and followed through. For example, if focusing on sustainability, cost, and time cannot come across as the main constraints, they must be dealt with case by case unless the client defines a minimum criterion for these.

Engineers and architects seldom hold the main responsibility for risks related to time, cost, or quality, but they hold the main responsibility for informing the client of the alternatives available and the consequences, risks, and assumptions following a decision. It can be somewhat uncomfortable to focus on factors beyond cost or time, which may not be expressed in quantitative terms. Focusing on adding value to the project could be difficult for some to handle, as this is seen as more subjective and not as definitive as, say, cost and schedule. This is when a method such as CBA is important to allow teams to account for qualitative and quantitative information to describe the value of alternatives.

General contractors often have an overview of the cost, time, and opportunities for creating alternative solutions. They also have contact with many of the experts, such as subcontractors, superintendents, and craft workers. Furthermore, they have intel from suppliers and can provide advice to counter the volatility in the supply chain, especially on long lead items due to global challenges. Therefore, general contractors are also responsible for communicating the project's priorities to the wider team and gathering information on alternatives. In addition, general contractors can provide information to inform the design alternatives regarding constructability, maintenance, and long-term performance of facilities.

For users in a traditional setting, the feedback they provide is extremely difficult to incorporate without a structured decision-making process. Therefore, users need to be proactively involved in the process to specify criteria based on "needs" and "wants" and not wait until the decision is made to provide input. If the expectations of the owner and users are clear, the architect, engineers, and contractors can work on specific decisions together. This means that from the very beginning, the decision-making process needs to be defined, the responsibility of every role must be clarified, and specific stages need to be determined to set up the process structure. Due to different perspectives, the team will need to adopt a method that helps them understand each other and see the overall impact of the decision within the project. Transparency and learning about the difference by comparing the attributes of the alternatives will help the team instill a constructive conversation. Table 3 presents an overview of the roles and responsibilities.

Table 3: Traditional vs. recommended roles and responsibilities

	Traditional	**Recommended**
Owners' responsibilities	Focus on time and budget. Unstructured and slow when making decisions.	Be specific in values and set a shared vision. Own the decision processes and related risks. Advocate for diverse perspectives and including users.
Architects'/engineers' responsibilities	Provide one design solution and push for acceptance (point-based decision-making). Make decisions *in silos* without gathering expert information.	Help structure a transparent process by setting up feasible alternatives (set-based decision-making). Include experts from the execution phase.
General contractors' responsibilities	Evaluate decisions based on cost and time. Make decisions *in silos* without gathering expert information.	Gather information on alternatives based on value creation. Add information on risk, opportunities, and cost. Include cluster experts in making decisions.
Users' responsibilities (if included in the decision-making process)	Feedback on decisions already made by others (reactive).	Be specific in must haves and nice to haves as input to decision-making (proactive).

CONCLUSION

This paper documents the concerns of different stakeholders in implementing a collaborative decision-making process. Our recommendations are based on the three case studies, and we reference the traditional decision-making process to demonstrate the contrast. In this research, we conclude that owners are responsible for defining a shared vision to guide decisions, architects/engineers are responsible for creating feasible design alternatives, general contractors/trade partners are responsible for providing their perspective in the evaluation of alternatives and providing pricing and schedule impacts, and users are responsible for distinguishing between "needs" and "wants." In addition, consultants and/or trainers to support the team are likely needed because (1) even when the stakeholders are aligned through a collaborative contract, teams struggle with decision-making, as roles and responsibilities are not defined in advance, and (2) most people will need to learn a sound decision-making method, such as CBA.

The discussion of the roles and responsibilities within a project team is relevant and far from being resolved. This research is somewhat limited, and we encourage other researchers to document and experiment with different roles and responsibilities among construction team members to allow them to draw knowledge and expertise from a variety of project participants and support the creation of value using innovation. The authors believe that only through this inclusive and collaborative process can more sustainable designs be created in construction projects.

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ANALYSIS OF LEAN CONSTRUCTION CASES IN IRELAND

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ABSTRACT

The purpose of this paper is to identify what lean tools and techniques construction companies are using in Ireland and what common challenges and benefits exist for their implementation. Currently, research on lean construction (LC) implementation in Ireland is weak and fragmented, and this paper will help address this gap in literature and provide an overview of this activity.

Through analysis of the 17 cases gathered through the Lean Construction Ireland (LCi) "Book of Cases 2022," this paper identifies that most case studies originated from large, privately owned, general contracting companies and a wide array of lean tools are being used. All cases indicated benefits from LC, the most common being an improvement in quality, then cost, followed by time and safety. Covid-19 was found to be a catalyst for lean initiatives. Leadership support, staff training, piloting lean initiatives, developing a collaborative culture and continuous improvement were identified as important factors for implementing and sustaining LC. Although the sample size is limited, this paper does provide a useful indicator of overall LC activity in Ireland that will be of interest for academics and practitioners to consider and build upon.

KEYWORDS

Case study analysis, Lean tools, culture, leadership

INTRODUCTION

Ebbs et al. (2015) suggest that LC field research and case studies are very limited in Ireland. Over the last five years, a book of cases has been published annually by Lean Construction Ireland (LCi), each containing a collection of case studies from the Irish construction industry that demonstrate the challenges and outcomes of implementing LC. However, most of these case studies have not been incorporated into formal research papers. The first author of this paper is a director with LCi and was the editor for the LCi Book of Cases in 2022. The aim of this paper is to utilise the Book of Cases 2022, to identify what lean tools and techniques companies are using in Ireland and what common challenges and benefits exist for their implementation. An overview of LCi will be provided initially to set the context, followed by a literature review. The research methodology will then be outlined, followed by an overview of the Book of Cases 2022. The results will then be presented followed by a discussion and conclusion.

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In 2018, the LCi community of learning and practice became a company limited by guarantee. Its objectives are to promote lean thinking and practices in the Irish construction sector by making available information, guidelines, and support. With directors from both industry and academia, LCi has approximately 90 corporate members as well as hundreds of individual members. LCi has facilitated over 50 LC webinars, published five Book of Cases, and is focusing on capability development by sharing best practices and helping upskill and develop the workforce through its activities. By identifying lean construction case studies in industry and compiling them into book-form for annual publication, LC practices have been shared throughout the construction sector. Through academic research, the value of these cases can be strengthened so that further insights can be gained and disseminated via various research groups such as the IGLC.

LITERATURE REVIEW

In this literature review, LC will be introduced and the importance of collaboration between industry and academia highlighted. The topic of learning will be discussed as well as the various LC tools and techniques used. Gaps in research from an Irish case study perspective will then be discussed. The benefits of LC will be outlined and key factors for LC successful adoption reviewed.

Our understanding of lean principles and LC is evolving. Lean manufacturing has been studied by academics for 30 years and the MIT International Motor Vehicle Program (IMVP) benchmarked Toyota's superior performance and coined the phrase lean to describe this system (Womack et al., 1990). The findings of this prompted the formation of lean groups by practitioners including the Lean Enterprise Institute in the USA (www.lean.org), the Lean Enterprise Academy in the UK (www.leanik.org), and 15 other non-profit institutes across the globe (Netland & Powell, 2016). Similarly, the International Group for Lean Construction (IGLC) was formed to develop new principles and methods for product development and production management, specifically tailored to the AEC industry, but akin to those defining lean production that proved to be so successful in manufacturing (IGLC.Net, 2023).

The call for change in the construction industry has been well documented in terms of how this sector operates (Egan et al., 1998; Koskela & Howell, 2008; Latham, 1994;). This paradigm change is still ongoing today. The main objective of lean production is to eliminate waste by reducing or minimizing variability related to supply, processing time, and demand (Shah & Ward, 2007). In construction, the role of Lean is to improve the processes and delivery methods of a project to better meet the needs of the owner through the elimination of waste and non-value adding activities (Ghosh & Burghart, 2021).

The collaboration between industry and academia through the IGLC and communities of practice like LCi are promoting change in the industry. With the increase in the adoption of lean tools and principles in the construction industry, it is pertinent to investigate the experience of the contractors to facilitate widespread adoption of lean for improvement of industry performances (Ghosh & Burghart, 2021). Companies that collaborate with academia have shown to prosper (Pizam et al., 2013). Research has indicated that construction management research has not made a lasting impact on the sector because of misalignment of research methods and problems targeted with developments in the industry (Koskela, 2017). Collaboration between universities and industry is not straightforward and Aouad et al. (2010) suggest a "shared pace whereby the work being undertaken by the research community has meaning in both the academic and industrial world." Case studies are a suitable method to extract data for complex situations (Taggart et al., 2019) and can facilitate a meaningful collaboration between industry and academia.

Learning is important for a lean construction team. Organisational learning and knowledge creation are interdependent as learning is a dynamic process that promotes the knowledge creation process (Lyles, 2014). Lean teams must be aware of practices for improving knowledge generation that can improve construction processes, eliminate waste, and pursue perfection (Zhang & Chen, 2016). When LC managers implement a lean tool, they unintentionally facilitate the knowledge creation. Therefore, attention should be paid to keep new knowledge recorded and to build a more holistic and efficient knowledge management system (Zhang & Chen, 2016). Case studies are a useful way of recording knowledge created from lean tools.

A broad range of LC tools exist to reduce waste and improve efficiency. For example, Zhang and Chen (2016) considered lean techniques that have transferred from lean manufacturing including concurrent engineering, daily huddles, Kanban, value stream mapping, quality management tools including Plan Do Check Act (PDCA), Just in Time (JIT), Total Quality Management (TQM), and Human Resource (HR) management. Examples of other LC tools are 5S and First Run Studies (Noorzai, 2022). In addition, Schia et al. (2019) reviewed the topic of Artificial Intelligence (AI) for the construction industry and indicated that AI can automate several operations to increase efficiency and thus minimise waste.

LC implementation case research in Ireland is limited to a few academic papers and there is no consolidated overview. Existing literature relates to the Line of Balance production planning (Taggart et al.,2019), The Last Planner System (Power & Taylor, 2019) and the integration of Lean and BIM processes (McHugh et al., 2019). A cloud based digital LPS is also reviewed by McHugh et al. (2021a) as well as reality capture (McHugh et al., 2021b). By carrying out academic research on the Book of Cases 2022, it is hoped that the range of tools and techniques currently being used in Ireland are identified and associated benefits and challenges uncovered.

In relation to the benefits from LC, Lavikka et al. (2019) identified an improvement in build time, cost, quality and health and safety, when comparing hospital construction projects that have implemented lean construction with ones that don't. Frequently, research focuses on the success of lean processes and less on the obstacles to their deployment (Simonsen et al., 2014). By identifying and understanding the barriers to implementing change and LC, more opportunities are provided to succeed and recognise the need for organisational change (Cano et al., 2015; Perez & Ghosh, 2018). Sarhan & Fox (2013) identified the top three barriers to implementing lean as the lack of adequate lean awareness and understanding, culture issues and a lack of top management commitment. This is further supported by Sarhan et al. (2016) who identified 12 critical success factors for implementing LC, such as providing education and training for lean construction, promoting a culture of teamwork and adopting continuous improvement. Xue et al. (2014) identified the importance of collaboration and culture to support innovation also. Thus, education and training, culture, collaboration, top management commitment and continuous improvement have been identified in literature as key factors for LC adoption. By assessing LC cases in Ireland, it can be determined how applicable these factors are in this local context.

RESEARCH METHODOLOGY

The aim of this paper is to identify what lean tools and techniques companies are using in Ireland and what common challenges and benefits exist for their implementation. Figure 1 below outlines the research methodology used, which initiated with a survey used to get preliminary data and finalise the case study template. Case studies were then gathered and completed. The last stage was qualitative analysis of the cases using NVIVO software.

To utilise the LCi Book of Cases for this research, the first author, who was also the editor for the Book of Cases, arranged a short, online survey of LCi members to get some insights into the relevance and suitability of the LCi Book of Cases and identify opportunities for improvement. Survey feedback was reviewed, and various improvements identified for the book of cases format and template. During 2022, 17 LC cases were drafted by 16 companies and submitted to the editor. Following an interactive process, all complete cases received in the revised template were then refined by the editor, proofed, categorised into themes, and then compiled into a Book of Cases 2022 publication (Lean Construction Ireland, 2022).

A qualitative analysis of the Book of Cases 2022 was then undertaken. According to Burke, Johnson & Onwuegbuzie (2004), qualitative research is useful for studying a limited number of cases in depth and for understanding people's personal experiences of phenomena in local contexts in vivid detail. For case study analysis, NVIVO software was used for coding of the cases and various qualitative analytical tools such as word frequency, word searches etc. Discussions also took place with industry-based case authors to get a deeper understanding of various cases and to address clarifications. This data and analysis helped identify LC tools and benefits. Emerging themes across the 17 cases were also identified (Braun & Clark, 2006). Building on this work, a matrix was then developed to capture the key elements of each case for ease of further analysis. This matrix will be discussed later and lists the case number and key details of each case study, including indicative benefits.

Figure 1: Research Methodology

PRELIMINARY SURVEY

The first author arranged a survey with all LCi corporate and individual members to identify if improvements could be made to the book of cases format so that a case study template could be finalised. This survey identified that 72% of respondents felt that their company was at the early to intermediate stage of lean adoption. 93% of respondents agreed/ strongly agreed that the book of cases was appropriate to their organisation and was a valuable asset. In addition, 92% of respondents said that they read at least a few, if not all the case studies.

Several recommendations were made by respondents to improve the book of cases. These recommendations included the addition of an introduction section, which would provide a summary of the cases, a dedicated section on BIM/Digital Technology, making case titles clear and breaking cases into categories. These findings from this survey were implemented and facilitated the refinement of the case study template used for the Book of Cases, 2022.

CASE STUDY COMPILATION

Based on survey feedback, a new standardised template for the cases was developed with the following headings: case study title, company overview, overview and background of lead initiative, lean initiative undertaken, lean initiative improvements and impact and lessons learned. In addition, an "Introduction Chapter" was included in the Book of Cases and appropriate chapters/ themes were formed to gather related cases and make the book easier to navigate.

In 2022, a call for abstracts was issued to the construction sector through emails and social media channels. The editor recommended that all abstracts were progressed to full cases by the company-based authors using the new case template. Cases were then reviewed, edited, and refined by the editor, following consultation with the case author. All cases received were included in the Book of Cases, categorised into themes and then the book was compiled, proofed, printed, and circulated.

CASE STUDY OVERVIEW

In this section, an overview of the 17 case studies (Lean Construction Ireland, 2022) will be presented. The cases have been categorised into the following themes: Operational Excellence, Digitisation, Modern Methods of Construction and Resource Management. See the Case Study Matrix in Table 1 at the end of the paper for a full case overview. Cases have been numbered, where C1 denotes the first case, C2 the second and so on.

OPERATIONAL EXCELLENCE CASES

The following is a summary of the operational excellence related cases:

- C1: The Coffey Pillars of Lean were presented, including 6S, 8 Wastes, Visual Management, Standard Work, DMAIC and the Last Planner.
- C2: Duggan Brothers identifies 107 tasks for improvement through the involvement of 27 senior managers across eight departments.
- C3: Hawthorn Heights mapped out processes, used the LCi Lean Audit Tool and achieved significant improvements.
- C4: Kirby's developed a framework using DMAIC for determining the cost of quality and utilised Fish Bone diagrams and 5-Why tools.
- C5: Mace improved safety, quality, productivity, and schedule compliance by using an A3, 5S and 8 waste tools.
- C6: OPW developed a Dynamic Purchasing System and decreased supervision and management costs.

DIGITISATION CASES

The following is a summary of the cases listed under the digitisation theme:

- C7: Arup provided an overview of their HIVE (Human Immersive Virtual Environments) which has helped clients gain a better appreciation of proposals.
- C8: Errigal used DMAIC and digital tools to develop a data driven framework to identify and eliminate inefficiencies in processes.
- C9: John Paul Construction demonstrated the benefits of using the Last Planner and the cloud-based Field View system for achieving project milestones.
- C10: Mannings Construction Group outline how they have utilized digital solutions such as dashboards, timelapse cameras, vehicle recognition systems and the common data environment to improve overall efficiency.
- C11: SISK demonstrated the use of Artificial Intelligence (AI) to automatically read form data. Through automation and digitization, significant time is being saved and the quality of data capture has improved.
- C12: Walls first case study outlines the significant benefits of upgrading IT infrastructure and software to provide a better controlled environment with reduced administration and energy overheads.
- C13: Walls second case demonstrates employee accessibility of BIM 3D models using Dalux BIM mobile viewer as well as a reduction in waste.

MODERN METHODS OF CONSTRUCTION AND RESOURCE MANAGEMENT CASES

Cases related to modern methods of construction and resource management are:

- C14: ACB group focus on Modern Methods of Construction (MMC) using lean principles. They utilized BIM and the PDCA tool to develop its prefabrication model further by seeking to incorporate additional building finishes.
- C15: Horizon Offsite increased productivity and reduced non-conformances through workplace and factory optimization, performance tracking and data visualization.

- C16: Ardmac used a High-Performance Team model and human behavior was improved to promote collaboration and increase productivity.
- C17: DPS Engineering developed an effective resource mobilisation process using lean thinking and the DMAIC tool.

RESULTS

This section will analyse the profiles of companies that submitted cases as well as the lean tools used. In addition, indicative benefits from LC implementation will be provided. The themes that emerged from qualitative analysis will then be presented.

COMPANY PROFILES AND LEAN TOOLS USED

Table 1 at the end of the paper shows a matrix, which summarises the key elements of the case studies. This matrix lists the case number, company name, size, type, sector case title and tools used. It also identifies the theme that the case was aligned to and the indicative benefits from a time, cost, quality, and safety perspective. In terms of company profile, six companies were small to medium sized organisations (SMEs), with less than 250 employees, while ten companies were large. Only one company was publicly owned (C6), the rest were privately owned. C6 was the only client-based company represented in these cases. A multitude of sectors were represented with the most common being general contractors.

A wide variety of tools were identified within the case studies. Tools used more than once were identified and sorted by frequency and are presented in Figure 2 below. The most common tools used were DMAIC and 8 wastes, followed by BIM/ 3D viewing, LPS, 5S, and the use of Cloud Data. Value stream mapping or process mapping, PDCA, A3, and Artificial Intelligence were other tools used in two case studies. Overall, 10 tools were referenced in at least 2 of the 17 cases.

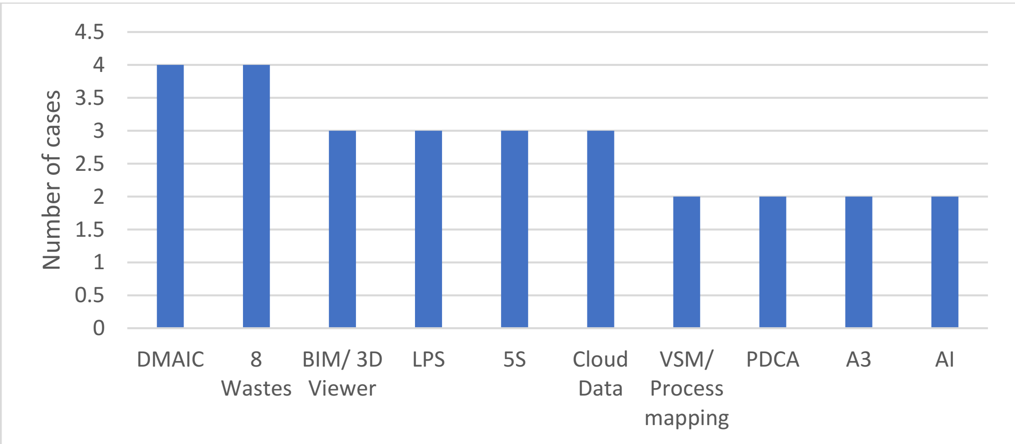

Figure 2: Lean Tools Referenced in More Than One Case Study.

BENEFITS

A range of benefits were identified in the case studies as listed in Table 1. In Figure 3 below, the main benefits are presented in terms of the percentage occurrence in the cases. 88% of cases indicated an improvement in quality, 71% of cases referenced a saving in cost, 47% indicated a saving in time and 35% had a safety related benefit. All cases except two (C4, C7) had at least two benefits indicated.

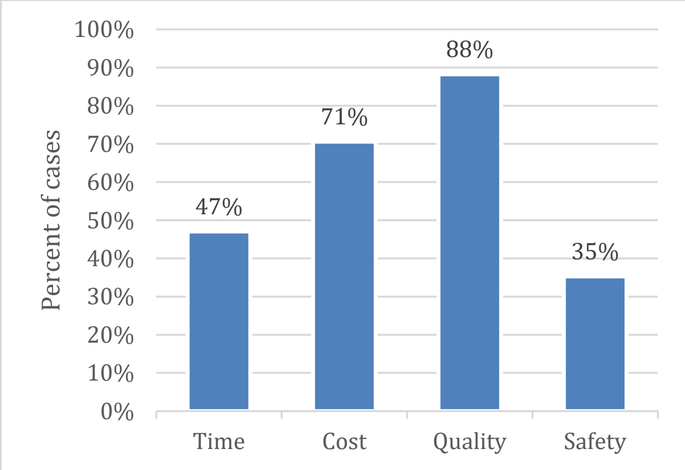

Figure 3: Benefits Identified from Lean Initiatives.

KEY THEMES IDENTIFIED

Through iterative thematic analysis throughout this study, several key themes were identified in the cases, relating to potential enablers, challenges, or barriers to lean implementation. These themes are: Covid-19, piloting initiatives, training, culture, and leadership.

Covid-19 was found to be a strong catalyst for change and an opportunity to put in place continuous improvement and lean plans (C1). It also helped drive the adoption of cloud technology to facilitate remote working (C13). Due to Covid-19 related resource constraints and rapid sudden start-up of projects, lean was applied to resource planning to improve resource mobilisation (C17).

Piloting lean initiatives on a smaller scale to prove the concept and get buy in was a regular and robust approach to rolling out change initiatives (C1, C2, C6, C11, C12). C2 used the Deming cycle (Plan, Do, Check, Act) to implement change and allow for a dynamic and flexible outcome.

Training of staff has been identified as a key enabler to lean adoption. Training has been referenced in 11 of the 16 companies (69%) as a key enabler to lean implementation and continuous improvement (C1, C2, C4, C5, C7, C8, C10, C11, C12, C15, C17). A structured approach for lean principles was sought through lean green belt training, attending LCi webinars (C1) and LPS (C1, C10). Internal training was carried out on IT systems and dashboards (C2) as well as lessons learned (C2, C10). A training programme on the cost of quality was an outcome for C4, while training on understanding waste was carried out for C5 and on virtual reality software (C7). In C8, a survey was carried out to identify what training was required by the staff. Training a machine learning model was also completed (C11). In addition, enabling staff to utilise lean and digital tools was seen to be key to improving capability (C12).

Culture was referenced in seven cases. A continuous improvement culture was referenced in C1, while a culture to improve collaboration and reduce silos was referenced in C4, C5 and C6. To sustain change and improvements, culture was seen as important (C8, C15), while generating a proactive culture was referenced in C9. Companies need to be inclusive with staff to facilitate lean adoption, so that there is buy-in to the change and staff need time to reflect on change and consider the impacts and upskill as required (C2, C8, C10). Bottom-up changes from new staff should also be facilitated (C11) and start with easy wins (C2). Tools are available and effective to specifically improve the performance of teams (C16). Overall, the case studies reveal a desire for a continuous improvement culture through collaboration, inclusion, upskilling and the use of digital and lean tools.

Leadership is also identified as an important factor in lean initiatives and was referenced in six cases. Leadership training was referenced (C1), while leadership support and buy in also featured (C1, C14, C16). Company commitment and leadership were considered in C4. Leaders fostered and maintained a creative and innovative environment (C12) and were convinced that change was needed (C15).

DISCUSSION

This study analysed 17 cases contained in the LCi Book of Cases 2022 to get an insight and overview of current tools being used in Ireland as well as associated benefits and challenges. This research also helped address the lack of case study research in Ireland. The preliminary survey results indicated that the Book of Cases is a valuable asset to construction companies. It has also connected academia and industry (Pizam et al., 2013) in a meaningful way (Aouad et al., 2010) and facilitated the investigation of experiences of contractors. Doing so has helped the adoption of LC in the construction industry as recommended by Ghosh & Burghart (2021).

A broad range of LC tools have been researched by academics (Noorzai, 2022; Schia et al., 2019; Zhang & Chen, 2016). In Ireland, LC case study research is limited to a few academic papers by Taggart et al. (2019), Power and Taylor (2019), McHugh et al. (2019), McHugh et al. (2021a) and McHugh et al. (2021b). This paper has further developed and consolidated case study literature in Ireland and has highlighted associated tools, benefits, and themes from 17 cases in 2022.

As cases were mainly from large contractors, there is scope to potentially target more diverse stakeholders in future so that a broader perspective is gained. All cases reviewed indicate multiple benefits for LC implementation, including improvements in cost, schedule, quality and health and safety. These benefits align to those of Lavikka et al. (2019). The themes that emerge from the cases include the significance of Covid-19, piloting lean initiatives, training, culture, and leadership in these case studies. These themes align to those identified in literature (Lyles, 2014; Zhang & Chen, 2016). Covid-19 has facilitated improvements in LC and piloting initiatives has helped improve buy in. Training was seen as instrumental for LC adoption. A collaborative culture with support from leadership is also seen as important for LC adoption. These findings support those from Sarhan and Fox (2013), who identified the top three LC barriers as lean awareness (training), cultural issues and lack of top management commitment.

Findings from this study resonate with those from the study of Ebbs et al. (2015), who found that short term wins are the primary focus rather than a management philosophy for LC, and that practice has not caught up with the theory. Although LPS has been used in Ireland and the potential benefits of using Line of Balance highlighted (Taggart et al., 2019) no reference to takt planning exists and there is still a lot of progress needed to enable a more mature, production management approach to LC. The Irish lean construction community will need to actively monitor trends and developments overseas so that they can be incorporated into practice and help evolve LC activity.

Although six operational excellence focused cases were developed in 2022, there was no consistent approach on how LC is adapted into companies. It appears there is a mixed approach, both from the top-down through policies and strategies and from the bottom-up through pilot projects. Ward and Caklais (2019) concur and believe that ad hoc deployment of tools and techniques is frequent, but business transformation is very rare. They examined the first use of the new international lean standard ISO 18404:2015 and suggest that it could act as a useful roadmap for those seeking to transform.

Although this study has provided an overview of multiple LC cases in Ireland and associated benefits and key factors, it is limited to a snapshot in time. Further similar research on previous and future cases will help develop a deeper understanding of LC activity in Ireland so that its maturity can be thoroughly assessed and trended over time. In addition, the maturity of various tools was not part of this study, and the assessment of benefits of LC is indicative only. Further research on tool maturity and benefits would be helpful.

However, the Irish construction sector appears to be moving in the right direction, where culture and leadership are important elements for organisational change such as LC adoption. Published case studies are a valuable resource to both industry and academia. Further insights have been identified and shared with academia through this paper that builds upon existing literature. By continuing to carry out academic research on LC cases, further consolidation and insights can be uncovered to help improve LC adoption and maturity.

CONCLUSION

This paper has achieved its purpose of identifying what lean tools and techniques construction companies are using in Ireland and what common challenges and benefits exist for their implementation. The Book of Cases is an asset that shares insights and helps facilitate collaboration between academia and industry and help the adaption of LC. Indications are that Ireland is at an early to intermediate stage of LC maturity, as companies are deploying lean tools to reduce waste, rather than taking a wider production management approach to LC adoption. Findings relating to the lean tools, benefits and challenges support existing literature reviewed, and highlight the importance of training, culture, and top management commitment.

LC activity in Ireland is still at an early stage of adoption where the focus seems to be on short term wins, rather than on long term transformation. Opportunities to develop a lean production management approach exists, and consideration should be given to a more standardised way of business transformation.

As this paper focuses to the Book of Cases 2022, it is limited to a snapshot in time. It is recommended that further academic research on future and past book of cases should be carried out to get a deeper appreciation for LC activity in Ireland as well as to consider ways to assess tool maturity and LC benefits in a more comprehensive way.

Covid-19 has been a catalyst for digitisation of many systems and processes, which has provided new opportunities for streamlining processes and reducing administration. A more collaborative and team focused approach for LC adoption is suggested from this study, through the inclusion of all stakeholders in change initiatives, which leads to better engagement, understanding, adoption and sustainability of improvements. By developing the enablers of leadership, training, and cultivating a collaborative culture, the focus can go from individual LC initiatives to the overall creation of effective production systems.

ACKNOWLEDGMENTS

We would like to thank all authors and companies who submitted cases to LCi in 2022 and allow the compilation of the LCi Book of Cases. Without your openness and generosity, this paper would not have been possible.

Table 1: Case Study Matrix

No.	Company	Size	Sector	Case Study Title	Tools Used	Time	Cost	Quality	Safety
C1	Coffey	Large	Civil Contractor	Lean and Collaborative Planning at Coffey	6S, 8 Wastes, DMAIC, LPS.			Q	S
C2	Duggan Brothers	SME	General contractor	Make the change and implement lean	8 wastes, VSM, LPS, DMAIC, 5S, FMEA, PDCA, A3, Pareto.	T	C	Q	
C3	Hawthorn Heights	SME	Civil Contractor	The use of process mapping and 5S to optimise tender success and profitability	Process mapping, 5S, LCI lean waste audit tool.		C	Q	
C4	Kirby Group	Large	M&E contractor	Framework to determine Cost of Quality on Construction Projects.	DMAIC, Prevention Appraisal Failure, SIPOC, fishbone, 5 Whys, 6M, Process Mapping, TQM.			Q	
C5	Mace Group	Large	General contractor	5S Project Improvement Programme	A3, 5S, waste walks.			Q	S
C6	Office of Public Works	Large	State Buildings	OPW Lift Replacement Programme	Two stage procurement framework, IPD.	T	C		
C7	Arup	Large	Consultancy	The Lean Approach to Immersive Technology at Arup	VR.			Q	
C8	Errigal	Large	Manufacture	Improving Productivity The Errigal Way	Big Data, AI.	T	C	Q	
C9	John Paul Construct.	Large	General contractor	The Grange Development	Last Planner, Field View, other digital tools.	T	C	Q	S
C10	Mannings Group	SME	General contractor	Mannings Construction's Digitalisation of Systems and Processes	Digitisation of systems and processes.		C	Q	S
C11	SISK	Large	General contractor	Capturing Quality Information Using Artificial Intelligence	AI form reading, Microsoft flow.	T		Q	
C12	Walls	Large	General contractor	Walls Construction Cloud Based Solutions Development	BIM 3D viewer.		C	Q	
C13	Walls	As above	As above	The Journey to Our Digital Transformation	Centralised cloud-based docs.		C	Q	
C14	ACB Group	SME	General contractor	ACB Manufacturing – Towards Modern Methods of Construction Using Lean Principles	PDCA, Prefabrication, JIT, BIM.			Q	S
C15	Horizon Offsite	SME	Steel Prefab.	Horizon Offsite – Adopting a CI mindset to their Design for Manufacturing & Assembly operations	DfMA, Visual Mgt., prefabrication.	T	C	Q	S
C16	Ardmac	SME	General contractor	Data Led Approach to Developing Lean Behaviours on Complex Projects	High Performance Teams.	T	C	Q	
C17	DPS Eng.	Large	Project mgt. and engineering	Development of an effective Resource Mobilisation Process using Lean Thinking	DMAIC for resource mobilisation process.	T	C	Q	

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WHEN WE DEVELOP COLLABORATION, WHAT EXACTLY DO WE DEVELOP?

Sol Skinnarland[1] and Trond Bølviken[2]

ABSTRACT

In this paper we will expand further on the literature focusing on collaborations within the construction industry. In the articles that are concerned with collaborative efforts, the authors present definitions. Often a common denominator is that collaboration is carried out by two or more parties to reach a goal. Little operationalization is offered in terms of understanding collaboration contextually. What are we actually talking about when we are concerned with collaboration, and in particular how to develop collaboration between actors in the construction industry?

This paper aims to discuss the term collaboration from the collective viewpoints of actors at a construction site, who consist of skilled workers and apprentices, supervisors, foremen and site management. The basis for this discussion is a previous review of collaboration in the literature, as well as previous research undertaken by the (first) author, which operationalizes collaboration in terms of six underlying dimensions.

The argument posed in this paper is that if correct measures were to be identified and taken to improve and develop constructive collaborative relationships between interorganizational actors on the construction site, we would need to address the term collaboration in greater depth. Rather than operating with an overarching and insufficient definition of "collaboration", we need to operationalize and sufficiently understand how actors themselves understand collaboration within a specific context.

KEYWORDS

Collaboration, interorganizational relationship, trust, communication, perspective-taking, motivation, the Last Planner System

INTRODUCTION

Collaboration happens when two or more people perform a set of actions that enables them to achieve a goal. Appley and Winder (1977) defined interorganizational collaboration as a process in which two or more firms work closely together to achieve mutually beneficial results. Jacobsen (2004) stressed the fact that entering a collaboration was a voluntary act in which interdependent contractors sought each other to fulfil the quest of achieving the desired results. Collaboration optimally takes place when actors enter a relationship where they display commitment towards each other, and where they value the team relationship as much as they value their own self-interest (Appley & Winder, 1977). Wood and Gray (1991) offered the following definition: "Collaboration occurs when a group of autonomous stakeholders of a

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problem domain engage in an interactive process, using shared rules, norms, and structures, to act or decide on issues related to that domain".

In terms of collaboration taking place at a construction site, the stakeholders, in question, are the contractors who participate in the project. They represent independent decision-making firms, they act voluntarily, and they are normally expected to follow a set of industry norms and rules for this type of collaboration. An underlying premise is that the contractors together engage in, and form, a voluntary change-oriented relationship, in which they produce the result, e.g., a building, together. Although industry rules, norms and structures may be implicit in the collaboration, contractors may still explicitly agree on rules and guidelines that will govern the collaboration in the specific construction project.

The above initial descriptive take on what constitutes collaboration, as often found in the literature, is in line with what the readers would have expected. From these initial definitions of collaboration, readers often perceive they have sufficient knowledge of the concept to start tackling any problems thereof, and to follow the author's argument towards a solution to improve collaboration. But is it necessary so? How can the industry know how to develop and strengthen collaboration without more in-depth understanding of what the concept implies? The argument put forward in this paper is that there is a need to develop knowledge as to what constitutes collaboration in the context of the construction industry generally, and specifically the collaboration taking place at the construction site, to initiate the correct measures to develop a collaborative effort. Because, as stated by Howell et al. (2004), "[p]eople are at the beginning, end, and center of projects". Thus, in this paper we offer an in-depth analysis of what constitutes *collaboration*, as viewed by the actors themselves at a construction site.

Researchers have been concerned with collaboration from different perspectives over the last decades. Alves et al. (2021) investigated how the language used in contracts might influence collaboration, specifically in terms of developing and implementing schedules. They found that contract clauses mainly focused on the compliance, and they found overall a limited mentioning about collaborative efforts beyond expectations in the clauses (Alves et al., 2021). Willis and Alves (2020) investigated the language used in construction contracts with the purpose of identifying the keywords commonly associated with collaboration. Interestingly, they found that in traditional contracts, such as design-bid-build contracts (DBB), there was a lack of language to support collaboration. In integrated-project-delivery projects (IPD), on the other hand, keywords associated with collaboration were employed in the contract clauses to promote collaborative behaviors and processes.

Salazar et al. (2019) pointed to the need to teach actors on the project how to make reliable promises. They built on the previous work by Salazar et al. (2019) on how to generate reliable commitments and proposed an updated version of indicators to measure and control the management of commitments in construction projects. Retamal et al. (2021) presented the results from a case study about construction projects in Colombia that demonstrated the importance of enhanced understanding with the linguistic action process. This resonates well with the argument in this paper, that a conscious and practical approach to the use of language is needed to establish a reliable commitment.

Davoudabadi et al. (2022) described a research project in the UK in which a Lean-BIM joint implementation effort at an engineering design firm was evaluated. They found several barriers to effective collaboration between Lean-BIM teams as well as a lack of motivation and desire to engage in the collaboration. This was explained by a lack of awareness of the mutual gains from such a collaboration. Other barriers reported were that Lean and BIM experts exerted different work mentalities and lacked a common approach to accomplish their joint task, hence; group think biases were detected.

Research has pointed to various measures that need to be considered to develop collaborative relationships. Salam et al. (2019) proposed that designers and contractors need to align their knowledge and views about the actual interactive processes to which they engage. In their paper, they emphasized a concern about the lack of knowledge about what participants did in the active collaboration process. Schöttle and Tillmann (2018) discussed the development of shared goals as a means to support collaboration. They found evidence that there was a positive functional relationship between goal-setting activities and a) increased communication and coordination, b) a guide for team action, and c) enhanced team motivation. Gomes et al. (2016) specifically studied collaboration in the context of the early design phases and discussed how shared understanding can serve as a basis for collaboration. In their paper, they developed a model about the process of building a shared understanding, in which the key features are: a) division of labor, (as a condition for collaborative actions), b) coordinated perception and situational awareness, i.e. understanding co-workers' situations, and c) mediated coupling and boundary objects. Garcia and Murguia (2021), stressed the need to understand collaboration not only in theory but also in practice. In their study, they aimed to investigate which factors influenced collaboration and they set out to develop a model for inter-organizational collaboration. They concluded that collaboration can be nurtured by improved operational capacity, taking measures to reduce uncertainty, promote trust and to apply a longer-term view in developing fruitful partnerships.

The above review shows that research on collaboration in the construction industry varies not only in terms of the specific topic of interest, but also in terms of which phase (design or making) in the collaboration process is being assessed and which actors are the focal point.

METHOD

The present paper builds on a recently published curriculum book written for master students in Norway, which summarized the findings of research that had been carried out over the past two decades. This research explored the crucial question: "What is good collaboration to you?", and this same question was directed to various actors at a construction site. Thus, the scope was to discuss the term collaboration from the collective viewpoints of actors at a construction site.

This paper further builds on previous research and practice by the authors as well as a review of recent IGLC papers. Firstly, the collective data gathered from observations, interviews, and surveys for the doctoral thesis of Skinnarland (2013) served as a starting point for the conceptual discussion on collaborative relationships in the construction industry. In her doctoral thesis, collaborative relationships were the focal point of the research. The author established six dimensions for the term collaboration, based on a literature review and research on the collaborative practices on and among the actors at a construction site. These six dimensions are described in detail from page 5 onwards. Secondly, we build the paper on a review of the authors' collected research on construction site production and management, in which collaboration is viewed more implicitly. And, thirdly, a review of recent IGLC conference papers containing *collaboration* in the title, was conducted for the sole purpose of establishing a knowledge base for writing this paper.

DIMENSIONS OF COLLABORATION

Much like the type of collaboration that takes place in a surgical suite, where different professionals collectively prepare for the actual surgery as well as post-surgery activities so that the surgical process does not result in an unsuccessful outcome for the patient, so can a similar collaboration process take place in certain situations at a construction site. For example, two carpenters can help each other lifting beams, one holding while the other carries out the work. The crane operator collaborates with the carpenters to lift materials to a specific area on the construction site.

The above examples, whether in a surgical unit or the loading of materials at the construction site, demonstrate a *simultaneous* collaboration, a slightly different type of collaboration than the collaboration on the construction site that most frequently takes place, which is more *sequential* in form (Kalsaas & Ose, 2017). In sequential collaboration, each trade carries out their tasks in a given order, up until a finished result is handed over to the client. For a more thorough understanding of this, we may view collaboration within the concepts of work flow and coordination. When studying organizations, we cannot escape the very basic premise that all organizations need coordination (Van de Ven et al., 1976). We can borrow insight from Thompson (1967) who proposed a theory of a hierarchical relationship in which the nature of workflow is determined by an increased level of task interdependence. According to Thompson (1967), workflow is either a) *independent* (or pooled), b) *sequential* or c) *reciprocal* in form. These are additive linkages as work flow interdependence increases (Van de Ven et al., 1976). Independent, or pooled, activities (Thompson, 1967), are activities which are carried out simultaneously but they are not linked to each other. An example would be a worker who installs windows on the first floor while another installs windows on the second floor. Sequential and reciprocal work flows are both mutually dependent. A sequential work flow is e.g. the first worker who installs the window, then the second worker installs the moldings. In a reciprocal work flow the activities will flow both directions as two of more workers rely on each other to accomplish the task, such as with the loading of materials.

Flow may be discussed in a psychological sense, as *intuitive qualities* (Bølviken & Kalsaas, 2011) as well as *production* (a physical sense). These two are different concepts, yet related. In the psychological sense, flow is the experience of an ultimate balance between task demands and perceived skills (Csikszentmihalyi, 1990). In production, flow is a physical reality. Kalsaas and Bølviken (2010) review the term flow in production conceptually and Kalsaas (2012; 2013) in later works develops the operationalizing of workflow. In measuring these two conceptual terms of flow, the authors found indications that for the skilled workers the measurement of perceived flow corresponds well with physical flow.

The point of departure in this paper is primarily sequential workflow and collaboration, where, for the work to be coordinated and carried out in an agile manner, with efficiency, good quality, and be performed only once, a *sequence* is required. All work activities carried out by the various trades on the construction site are part of a production where the result depends on everyone's input that is collectively given in a correct order. This brings us to the very core of collaboration in construction site production, dependence, in agreement with Thompson (1967). To complete the construction project, all trades depend on each other and each other’s input.

It is the question of *dependency* which urges the question of “What is good collaboration on the construction site?”. “What are the characteristics of interdisciplinary collaboration being perceived as good?” Researchers have been concerned with interdisciplinary collaboration, not only within the construction industry, but in all industries in which the project constitutes a form of work. A review of the literature (Skinnarland, 2013), that focused on collaborations at construction sites, suggested that characteristics of (good or bad) collaboration could be summarized into six dimensions of collaboration. In several Norwegian studies, skilled workers and apprentices, supervisors, foremen and site managers had been asked; “When do you experience good collaboration on the construction site?”. “What goes on between you and the other project participants when you perceive the collaboration to be good?” The answers to such questions revolved around: 1) the feeling of knowing each other, a sense of community and that they worked towards a common and known goal (dimension 1). Many interviewees described good collaboration as good involvement, good communication and a good flow of information (dimension 2). Others described collaboration as good when there was a large degree of trust between all trades and a lack of conflict (dimension 3). Still others reflected upon good collaboration as a feeling of being motivated, a feeling of being comfortable with each other and a feeling of having a good day at work (dimension 4). Others described further good collaboration in terms of experiencing a high degree of understanding, mutual respect, taking each other's perspectives and acknowledging each other's needs (dimension 5). When asking skilled workers, many reflected upon the experience of production predictability as proof of good collaboration (dimension 6). Skilled workers are concerned with the production flow and predictable work processes. When they experienced that, this was often to them perceived as good collaboration. In the coming section of the paper we will discuss each of the above six dimensions of collaboration and how they are intertwined to form good collaboration at a construction site.

A SENSE OF COMMUNITY AND FAMILIARITY

In inter-organisational collaboration, where trades are so dependent on each other's deliveries and efforts for the overall project to make good progress, many experience that the familiarity and common ground that develops, becomes a guarantee that the trades, to a larger degree, can work according to plan. Getting to know the people in the project gives the participants a sense of unity and a community. Experiencing community and togetherness affects well-being and the desire to help others.

It is, however, not sufficient for developing collaborative relationships, that project participants get to know each other on a social level. They also need to develop a familiarity professionally. "What is important to us to achieve trustworthy production flow?". Trades that communicate and articulate how dependencies between them affect production flow, invest in a type of professional conversation, which complements and strengthens the social relations and bonds between the project participants.

Early kick-off meetings *may* provide opportunities to develop relationships as project participants spend time together. As such, kick-off meetings, is a strategy to increase chances of success (Cooke & Hilton, 2015). Often participants report several positive experiences from kick-off meetings. They receive sufficient knowledge of the overall project, of the client's desires and ambitions, and what goals they will work on together to achieve success with the project. Project participants report a satisfaction with having met and gotten to know the other co-workers they will work with on the project (Skinnarland, 2012; Skinnarland, 2015). Such an early *sense of community, a we-in-this-project-feeling* and *a sense of familiarity* with both the project (and goals) and the participants from the various contractors, is often described as providing a sense of good collaboration. It may be possible to collaborate even without the tight social relationship; however, collaboration will gain from such familiarity (Skinnarland, 2013).

FEELING INVOLVED, GOOD COMMUNICATION AND FLOW OF INFORMATION

The second dimension of collaboration is *involvement* and *communication*. The basic idea of involving even the skilled workers and apprentices is twofold. One is that plan reliability increases as more informed input is provided, and another is that the more people take ownership and commit to following the plans, the greater the chances are that the work processes will flow well, and everyone will collaborate towards reaching the project goal. This last point addresses the giving and receiving of reliable promises.

Being involved increases understanding of the process and a feeling of knowing what one is a part of, what one's efforts contribute towards. Furthermore, the dependency between project participants calls for sufficient information sharing and a multi-trade approach to communication. Being involved and the way that project participants communicate within the project organization mutually influences and reinforces each other's strengths and weaknesses. Many of the actors interviewed in construction projects highlighted the driving force they experienced when they felt fully involved, which explained the association to involvement and communication.

Involvement and communication matter at the individual level, as it enhances well-being, and provides meaning to both the work itself and collaborative relationships. However, involvement also matters at the project level, as involvement strengthens the trade's will to help each other (the project community), to take more responsibility, and to be more committed. Coffey (2000) therefore emphasizes the importance of involvement and communication and states that involvement is an active manifestation of commitment.

PERCEIVED TRUST BETWEEN ACTORS

The third dimension of collaboration revolves around *trust issues*. Many researchers who have studied interpersonal relationships and interactions have been particularly concerned with trust, and the importance of trust in these relationships. Trust is built and torn down in a social and interactive process, in which the actors' interactions change the nature of the trust (Swärd, 2017). Social psychologists have studied what kind of behaviours between individuals creates or destroys trust whether at the individual or group levels. Trust understood at the interpersonal level can be defined as "the expectation of the other party in an interaction, the risk associated with believing them, and the acting on such expectations as well as the contextual factors, which either enhances or inhibits the development and maintenance of trust" (Lewicki & Bunker, 1996).

Given the great dependence, which exists between the actors at a construction site, there is a need to trust each other to experience a positive flow in their work production. Again, dependency requires that activities in an area are completed in a planned sequence as promised. Joint multi-trade planning makes apparent which trades will work on what, where and when. If performance (or quality thereof), or the timeframe is not in accordance with what was promised, there will be consequences for the trades who come later in the production process.

When promises are broken, project participants who take subsequent action based on the expectations of these promises will be disappointed. They become annoyed and frustrated. An occasional broken promise will most likely not significantly change the character of the trust. However, a pattern of broken promises can lead to broken trust. Thus, a high level of trust makes it easier to avoid conflicts in a project and easier to create a good collaborative climate. Again, the dependency on others to produce their project inputs demonstrates the sense of the participants' trust as a way to describe good collaboration.

FEELING OF BEING MOTIVATED AND HAVING A GOOD DAY AT WORK

The fourth dimension of collaboration is *motivation and well-being*. Many, when challenged to dwell upon the notion of good collaboration, express opinions in lines of; "to me good collaboration is feeling motivated and having a good day at work".

Many are highly motivated to take responsibility, to contribute to a joint project, and to work as a team and with other trades, to enhance production flow. Work motivation can be defined as "a set of energetic forces that originate both within as well as beyond an individual's being, to initiate work-related behavior and to determine its form, direction, intensity, and duration" (Pinder, 1998, p. 11). So, what is it that motivates those actors at a construction site? What motivates the site management is not necessarily the same as what motivates the middle management, which in turn may differ from what motivates the workers (Skinnarland, 2013). While the foremen are most concerned with daily production control and an overview of what is happening on the construction site, the site management is most concerned with organizational and structural conditions that facilitate optimal project implementation. By looking at what respectively middle managers (who are closer to production) and site managers (who take care of the administrative responsibility around project implementation) report in terms of what issues are of concern to them, we may deduce what it is that motivates them at work, and what they emphasize most in the collaboration.

In terms of worker motivation, Midtdal (2017) found that: a) piecework as a pay system is a motivational factor, alongside b) the working environment; and c) the feeling of self-efficacy. However, there is a need to voice caution regarding piecework. An incentive system based on piecework may be perceived as a motivator as long as production is flowing according to plan. If not, the pay system may result in decreased motivation, as lower pay becomes the central issue. Skinnarland (2013) also found that workers are motivated by being informed about the project, and by a sense of pride in their contribution to the project. All in all, it is useful for management to be conscious about what motivates the various participants in a construction project.

EXPERIENCING UNDERSTANDING, MUTUAL RESPECT AND PERSPECTIVE-TAKING

The fifth dimension of collaboration is *taking each other's perspective*. Therein lies a fundamental respect for the fact that what one's own trade produces affects what other trades can do. Respect is the core of understanding each other's needs and being able to understand each other's situation. Showing respect for others' finished work and showing a positive attitude towards finding solutions for each other are core values in communication between the trades. When, for example, supervisors get involved and discuss dependencies between trades and familiarize themselves with the needs of other trades, they may be able to help themselves too. When the trades communicate with a view to what others need and what is in the projects' best interest, they also consider their own needs. Thus, taking each other's perspective concerns two things. Firstly, it is drawing attention to the interdependence between the trades in order to achieve an optimal production flow. This is done by ensuring that the work is carried out in a way that meets the needs of all trades. Above all, the overarching point is doing work in the right order (sequence). Secondly, taking each other's perspective demonstrates positive attitudes. When project participants experience others consideration, and that others show interest in one's own trades' production and needs, this reinforces one's own willingness to meet the needs of others, and to show interest in other trades' production. Thus, one aspect of taking each other's perspective is purely result oriented, in that the trades collectively achieve a better construction process through finding optimal production solutions. Another aspect is the purely relational one, an interpersonal relationship in which the trades show each other respect and the ability to understand each other's point of view.

EXPERIENCING PRODUCTION PREDICTABILITY

The sixth dimension of collaboration concerns experiences of *predictability in work processes*. Particularly among skilled workers, there was an almost unanimous response to the question of what characterizes good collaboration, which concerned predictability. Predictability means that workers can bring materials and tools to a work zone and can start and finish work without disruptions or obstacles, and in line with what the plan dictates. Predictability is linked to the notion of flow. As explained with reference to Csikszentmihalyi (1990) one way of understanding flow is the positive psychological experience of devoting oneself entirely to work, free from distractions, and where the employee simultaneously experiences a good balance between professional challenges and own professional competences. Another way of approaching the concept of flow is by directing attention to the prerequisites that must be present to achieve production flow, where work processes proceed without distractions or stops. In line with the Last Planner System (Ballard, 2000) attention to the prerequisites for creating optimal flow takes place at several planning levels in the project organisation. Participants with roles and responsibilities further away from the actual production direct their attention to activities with a longer time perspective, typically two or three months in the future. For example, this could include planning the right staffing, or making sure to order deliveries with a long delivery time. Other types of prerequisites take place closer in time to the actual production, by other roles, such as supervisors and foremen. By working systematically with involvement at all levels of a project organization in the planning and preparation of upcoming activities, the total work and attention towards removing obstacles contributes to creating predictability. When skilled workers experience work predictability, they report well-being and a lower degree of stress in the work situation as positive consequences.

THOUGHTS ON CONCEPTS, DRIVERS AND CONCEQUENCES

As demonstrated, the concept of collaboration is multidimensional. Although researchers initially define collaboration, both in its simplicity as well as in its more complex and theoretical terms, we may summarize that there are multiple ways to understand collaboration. When these six dimensions of collaboration are highlighted in this paper, it follows from reviewing empirical studies of collaboration (Skinnarland, 2013). At the same time, reflections concerning what constitutes good collaboration, inevitably also conveys what the drivers are such as the conditions and premises under which good collaboration unfolds, and what the results are from this optimal collaboration. These are three ways of talking about collaboration which during reflection overlaps somewhat.

As an example, consider the trust dimension. We can summarize findings by saying that "Well, collaboration to me means that we have trust in each other» and reflects a consideration of what collaboration *is*. We can also summarize by saying that "Well, in order to experience good collaboration, we are dependent on creating trust in each other" as a reasoning around trust as a *driver* for, or a foundation for good collaboration. We can also summarize by saying that "Well, when we collaborate well with each other, we increase trust in each other", meaning that trust arises as a *consequence* of good collaboration. This is in line with Swärd (2017) who postulates that trust can be both the dependent and independent variables, as good collaboration conditions support trust and trust provides conditions for good collaboration. In similar manners, we can also reflect upon the other five dimensions of the concept of collaboration. Collaboration per se can be expressed by each of the dimensions. At the same time, all these dimensions are necessary conditions, or premises for creating and strengthening optimal collaboration, and also consequences of good collaboration.

Thus, to develop good inter-organisational collaboration at a construction site, we argue that it will be useful to gain more in-depth knowledge of what the dimensions of collaboration entail in the specific context of construction site production. What are we really talking about when we are concerned with involvement and communication? What does communication mean? How can we understand the communication process that takes place at the construction site? What do we really mean by the term involvement? How can we link the understanding of involvement to commitment? And how can we understand involvement and communication in terms of structural and systematic aspects on the one hand, and relational aspects on the other? And when we talk about trust, how can project participants use their language actively to articulate the network of commitments? (Slivon et al., 2010). How can motivation be linked to one's own interests and what is of value to oneself? What do we really mean when we talk about taking each other's perspectives? What importance do we attach to the mutual interdisciplinary dependence when we talk about taking each other's perspectives? And how can we understand predictable work processes by linking the discussion to prerequisites for healthy activities (Ballard & Howell, 1994), as stated by the Last Planner System? How can we reflect upon the concept of flow in a way that we gain a deeper understanding of what it really means when the project participants experience flow? By engaging in conversations concerning these and similar questions concerning collaboration, we argue that clarifying and understanding more in-depth the terms used daily may in fact constitute the best preparation for optimal collaboration processes.

MUTUAL IMPACT ON COLLABORATION

Following each of the dimensions in isolation, we may gain understanding of different ways to talk about collaboration. The argument so far is that taking collaboration as a concept apart, as demonstrated above, enables practitioners to direct discussion and attention to the aspects that really matter to enhance collaboration and collaborative efforts.

We have argued that one dimension of collaboration can form the basis for good collaboration and at the same time constitute a consequence of good collaboration. However, we may develop our argument further by stating that the dimensions of collaboration also may mutually influence each other. Meaning, we need to consider the dimensions of collaboration as interweaving aspects of each other. The dimensions influence and reinforce each other in both positive and negative ways. When elements in one of the dimensions falters, this can affect others, and conversely, when collaboration feels good in terms of one dimension, it also affects and strengthens other dimensions positively. A few examples may illustrate this point. Getting to know each other both professionally and socially is shown to affect the relationships of trust in the project. Involvement leads to greater commitment and well-being, which leads to more control both for the individual participant and for the overall project. In addition, greater commitment to produce according to planned activities leads to more predictable work processes. The degree of trust affects the willingness to share information, and involvement already from the outset of the project can contribute to establishing a good project culture founded on trust. Involvement and communication are prerequisites for developing trust. Another prerequisite is that commitments are kept, and that each trade delivers results according to the plan. Thus, a high degree of trust, and communication and information sharing, lead to more predictable work processes. This complexity may help explain the lack of an unambiguous "best practice" and why good production results are so difficult to reproduce from project to project; the results follow a number of complex intertwined factors that cannot be reproduced in exactly the same way.

LPS; COLLABORATION INTO A SYSTEM

Ballard et al. (2009) argued that a framework is needed to explore principles, functions, and methods for production control. The Last Planner System (LPS) principles "guide thinking and action, the functions it enables to be performed, and the methods or tools used to apply those principles and perform those functions" (Ballard et al., 2009). We argue that the in-depth knowledge of the multifaceted term *collaboration* as presented in this paper will benefit from being operationalized and put into collaborative practice within e.g., the LPS framework.

The Last Planner System (LPS) is a methodology for production control based on the idea of a need to actively coordinate human and material resources during the construction process. Ballard (2000) introduced the LPS as a critique of the traditional way of approaching planning, which commonly involved a centralized and detailed plan already from the outset of the construction project. The plan was produced by actors further away from the actual site production, thus separated from the production phase. LPS in large is concerned with involvement in interdisciplinary planning and continuous preparation for future production, through systematically removing obstacles to future work activities. LPS also has an inherent principle that the project participants, by getting involved and communicating with each other, commit to keeping promises made about production (Ballard et al., 2009). LPS is ultimately a methodology specifically for planning and managing the flow of construction site production. According to Bertelsen (2005), the Last Planner System thus provides for better collaboration across professional boundaries in the construction project.

Lookahead plans are central to LPS and the understanding of flow, discussed above. These plans fill the gap between master plans for the entire project and weekly work plans (Ballard, 1997). The main task in lookahead planning is to create healthy activities. That is, to remove any obstacles to the execution of the activities, so that the activities, when they have been transferred to a weekly work plan, can actually be carried out. Traditional weekly work schedules have been shown to be unreliable (Ballard & Howell 1994), and downstream production therefore traditionally is inherently unstable and unreliable. The idea of lookahead planning is to create predictable workflow. According to Ballard (2000), LPS increases reliability in three ways: 1) through lookahead planning and the preparation process, 2) through controlling for any previously planned work that needs to be completed; and 3) through involving and committing managers and employees. Ballard's description of the purpose and how to utilize lookahead planning is empirically supported (Fiallo & Revelo, 2002; Skinnarland, 2010; Skinnarland, 2013).

CONCLUSION

LPS has proven to be constructive, (see e.g., Salazar et al., 2019; Retamal et al., 2021), and contractors worldwide are currently carrying out construction projects within the framework of this methodology. However, implementing LPS has proven to be far more demanding than what one would have expected from a theoretical perspective. We argue that our discussion noted in this paper may reveal rationale for this observed experience that LPS promotes collaboration, but LPS is also dependent on collaboration itself.

Again, returning to the dimensions of collaboration, we need to pay attention to how project participants communicate. Do they understand each other's contributions and needs? Do they communicate with each other or is communication more in form of one-way information? Equally crucial is how the project participants behave towards each other. Do they act towards each other in a respectful manner despite professional disparity and different needs? The way that participants in the project talk to each other and behave towards each other may greatly impact how collaboration develops (Skinnarland, 2022). Previous research emphasizes the need for the project participants to focus their attention on structures and systematic aspects on the one hand, and the relational aspects on the other. These two perspectives need to be seen in parallel to enable strengthened collaboration (Skinnarland, 2013). Stated alternatively, the project collaboration needs to stand on two legs to be able to stand firmly. Thus, if research and practise are to succeed in developing good collaboration in project-based production, a necessary starting point must be to understand what we are really talking about when we talk about collaboration.

Every construction project consists of a plurality of roles, trades and various personalities, and although all participants should put in an effort to make sure collaboration works at its best, the management's role, for a fact, is prominent and absolutely decisive, in creating the best conditions for developing good collaboration. Research should particularly emphasise the manager role in attending to the multifaceted contents of collaboration. We also advise that future publications further develop in-depth knowledge of the term collaboration provided by the current paper. Future work should build on these findings and develop knowledge of how to improve collaboration in practice. One such framework to study collaboration in practice, however not limited to, is within the Last Planner System for production planning and control.

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ORGANIZING THE ARGUMENTATION FOR CHANGING THE DELIVERY SYSTEM USING CHOOSING BY ADVANTAGES (CBA)

Annett Schöttle[1], Rafael Guerreiro[2], André Haubrich[3], Michael Ditandy[4], and Fabian Behme[5]

ABSTRACT

Megaprojects contain strategic decisions that must be approved outside of the project. A clear and understandable argumentation is required to communicate and push through such decisions. As shown in the literature, Choosing by Advantages (CBA) helps teams create a shared understanding regarding a decision resulting in a strong argumentation of the decision outcome. Therefore, this research aims to better understand how CBA helps to make a strategic decision that impacts all project levels and creates the argumentation to get the approval of the management board of the company. This paper describes why and how the Deutsche Bahn team of the project Munich main station proceeded with the decision to change the project delivery system from design–bid–build (DBB) to integrated project delivery (IPD) while the project was already in different design stages using the CBA tabular method. As all authors (consultant and client) were involved in the research, participatory action research was used as the research approach. The paper demonstrates how CBA (1) helped to create a shared understanding of IPD, (2) helped to understand the scope of the multiparty agreement, (3) helped to organize the argumentation, and (4) helped to create trust regarding the argumentation.

KEYWORDS

Choosing by Advantages, collaboration, Integrated project delivery, megaproject, Munich main station.

INTRODUCTION

When starting a project, the owner must explain how the project will be delivered to begin the procurement process and get stakeholders on board. In megaprojects, there is the challenge that the time between defining the delivery system at the beginning of the project and the point when all stakeholders are on board can be years or even decades. Additionally, there is the challenge that megaprojects might not benefit from new management approaches that did not exist when the project started. Because megaprojects contain many unforeseen challenges and risks (e.g.,

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Flyvbjerg & Gardner, 2023; Priemus et al., 2013) as the project proceeds, they require adaptation to new findings from research and development to achieve the project goal.

Changing the delivery system impacts all organizational levels of a project, from the strategic level to the operational level. This requires courage from the owner and a project team that stands behind the change. Therefore, every member of the owner's team must understand the content of a decision and why the change is necessary, with all its advantages and consequences, to change the existing project structure. As some strategic decisions need support outside the project, a stable and comprehensive argumentation is required to get approval from the management board. Obtaining this approval can be a struggle if certain aspects are not considered or if the argumentation is not presented understandably.

Choosing by Advantages (CBA) is a multicriteria decision-making system developed by Suhr (1999) that differentiates between alternatives based on the importance of advantages. The most applied method of the CBA system is likely the CBA tabular method. Figure 1 shows the different steps of the tabular method. Studies show that using the tabular method helps project teams make stable decisions based on a shared understanding by including different perspectives that can contain conflicting interests (Arroyo et al., 2022; Arroyo & Long, 2018; Martinez et al., 2016; Parish & Tommenlein, 2009; Schöttle et al., 2019; Schöttle & Arroyo, 2017). Thus, having a reliable decision-making process is especially important for megaprojects "because the interests and power relations [...] are typically very strong, [...] given the enormous sums of money at stake, the many jobs, the environmental impacts, the national prestige, and so on" (Flyvbjerg et al., 2003, p. 7).

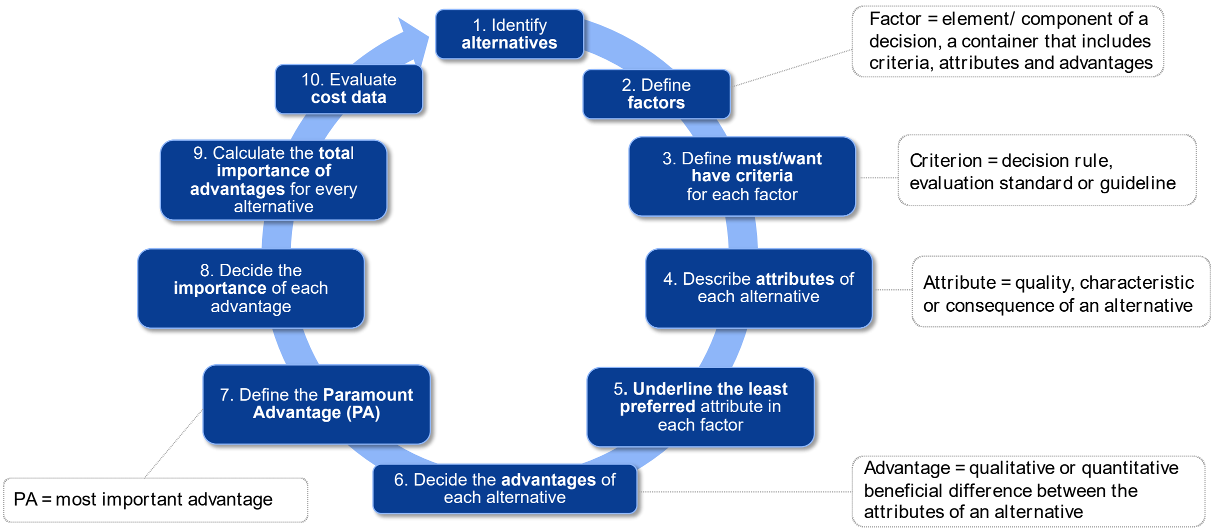

Figure 1: CBA Tabular Method (Schöttle et al., 2019, based on Arroyo, 2014)

A review of the literature shows that applications of CBA were explained in terms of tendering (Arroyo et al., 2022; Schöttle & Arroyo 2017; Schöttle et al., 2017) to decide between proposals, to decide between design alternatives (Arroyo et al., 2012; Arroyo et. Al. 2017; Arroyo & Long, 2018; Kpamma et al., 2017; Parrish & Tommelein, 2009), or for operational decisions (Martinez et al., 2016). Furthermore, all the papers mentioned above claim that the decision was made within the project and did not require approval outside of the project team.

This paper aims to show that CBA can help the project team organize their argumentation for a strategic decision that needs approval outside the project. First, the research method is explained, then the case will be presented, followed by an analysis and discussion of the collected data.

RESEARCH APPROACH

This research aims to better understand how CBA helps to make a strategic decision that impacts all project levels and needs to be approved by the organization. Therefore, the research question asks how CBA can help to reason the change in the delivery system.

Participatory action research was used as all authors (consultant and client) were involved in the research of changing the client system (Greenwood et al., 1993; Kindon, 2007; Tharenou et al., 2007). During the process, issues were identified and intervened on (Dickens & Watkins, 1999). **(1) Deciding to apply CBA:** The first author (A) briefly explained CBA to the project lead (H), then met with the project lead (B) and two cross-divisional leads (B, D) to explain the procedure of decision-making using CBA. In the meeting, the decision was made to apply CBA for a specific strategic question. **(2) Execution of workshops:** A series of workshops was executed to decide whether (Q1) integrated project delivery (IPD) should be applied and (Q2) which scope should be delivered using IPD to understand different perspectives better and, thus, create a strong argumentation for the approval process and the implementation of the decision. After each workshop, the participants defined the next steps for the following workshop. Because the workshops were assigned to two questions, there were two cycles. Due to availability and knowledge integration, there were different participants involved in the workshops. Table 1 gives an overview of the different participants involved. Overall, eight people from the project management team participated in the decision-making process. Figure 2 represents details regarding the position and the years of working experience of the participants. During the process, the first author (A) trained the team in CBA and guided them through the process. The second author (B) participated in all workshops. The third author (F) was partly involved in the second workshop and the final meeting. The fourth author (I) only discussed the decision outcome in the last meeting, and the last author (D) was partly involved in the workshops. The third and fourth authors were positively biased regarding IPD and therefore excluded themselves from the CBA workshops so as not to drive the discussion. **(3) Reflection of the procedure:** In February, the first author (A) briefly interviewed both project leads (F, I) regarding their experience as they were not or were only minorly involved in the workshops. At the beginning of April, an online survey with open-ended questions was carried out and answered by all eight participants to reflect on the procedure and to verify if the goal was achieved. The survey consisted of three parts. First, general questions were asked about the participants. Second, general questions were asked regarding strategic decision-making. Finally, questions were asked regarding the workshops. The first author decided to collect the reflection through a survey to minimize the biases such as anchoring or confirmation bias. Survey answers were analyzed based on content analysis (Mayring, 2010).

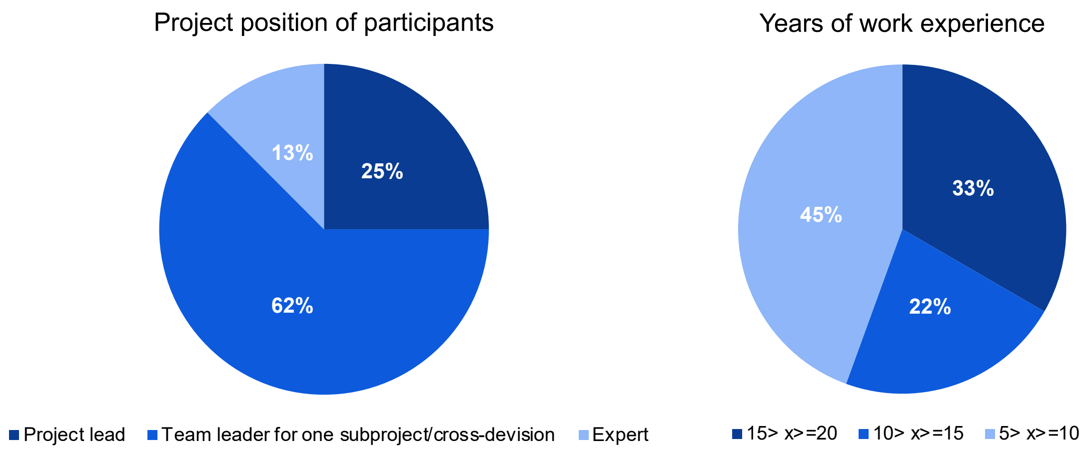

Figure 2: Details about Workshop Participants (excluding consultant)

Due to the degree of involvement in the workshops, all authors' knowledge regarding CBA was different. In short interviews, the second, third, and last authors were asked to give their opinion regarding the procedure of using the CBA tabular method and the outcome of the decision.

CASE STUDY

Due to the high traffic volume of the first core line of the city train (1.SBSS) in Munich, the line itself, as well as the main station, needs to be expanded. The 1.SBSS was opened in 1972, right before the Olympic Games, and was designed for 250,000 passengers per day. Today, up to 840,000 passengers per day (DB Netz, n.d.-a) use the line, often resulting in a two-minute *takt*, meaning that every two minutes a train is driving through the core line. This makes the 1.SBSS the busiest line in Europe. As the city, as well as the number of passengers using the line, will continue to grow, the line needs to be expanded by two more tracks parallel to the existing line called the second core line of the city train (2.SBSS) to overcome the bottleneck (see Figure 3). Both core lines contain underground stations at Munich’s main stations. The addition of the 2.SBSS to the infrastructure system means the main station has to be extended and modernized. Munich's main station is one of the biggest infrastructure hubs in Germany, with 450,000 passengers per day, 34 tracks overground, and 8 tracks underground. The main station is a megaproject itself that includes overground and underground work. Only buildings of 1.SBSS, the subway lines U1, U2, U4, and U5, as well as the tracks for the trains, and the historically protected track roof, will be sustained and remain in operation throughout the whole construction phase (see Figure 4). All other existing buildings will be demolished or updated, and new buildings will be built, including services areas, areas for restaurants, shops, and office space. Furthermore, the project contains a precautionary tunnel for another subway line (U9), the complete renovation of the track hall roof, and a new cross-platform roof. The anticipated cost for the main station (overground) is estimated at €1.2 billion.

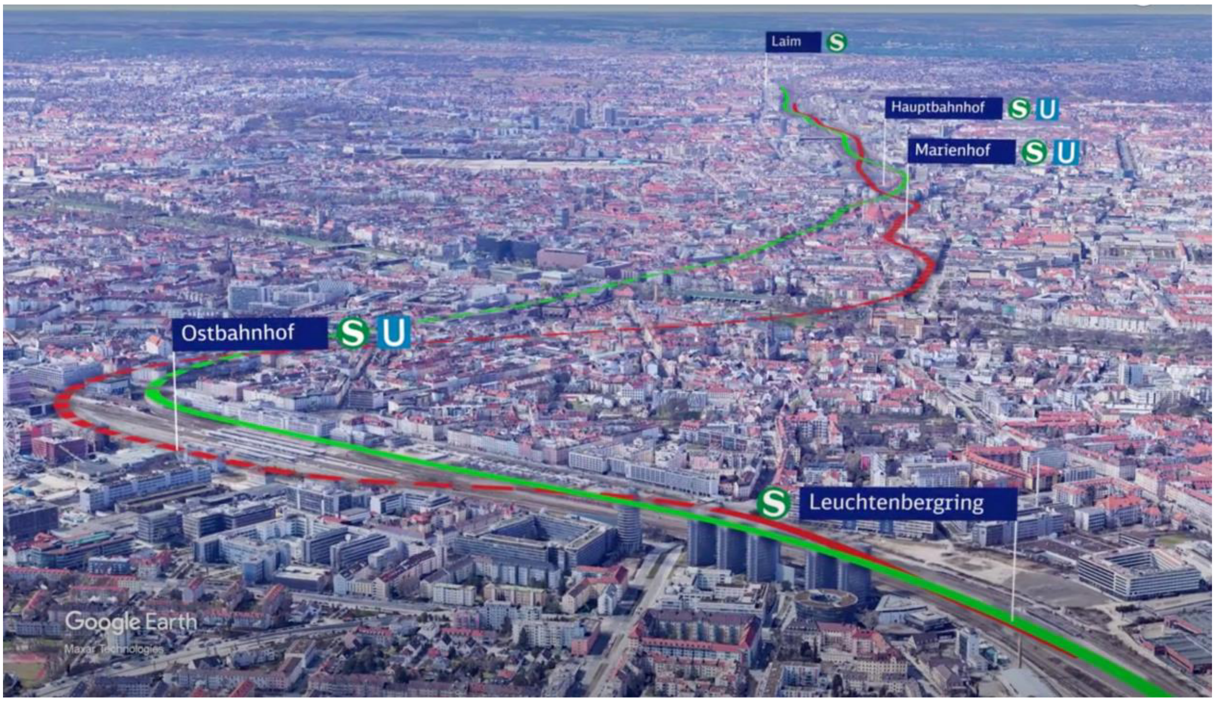

Figure 3: Routes of Both Core Lines (green represents the 1.SBSS, red represents the 2.SBSS) (DB Netz, n.d.-b).

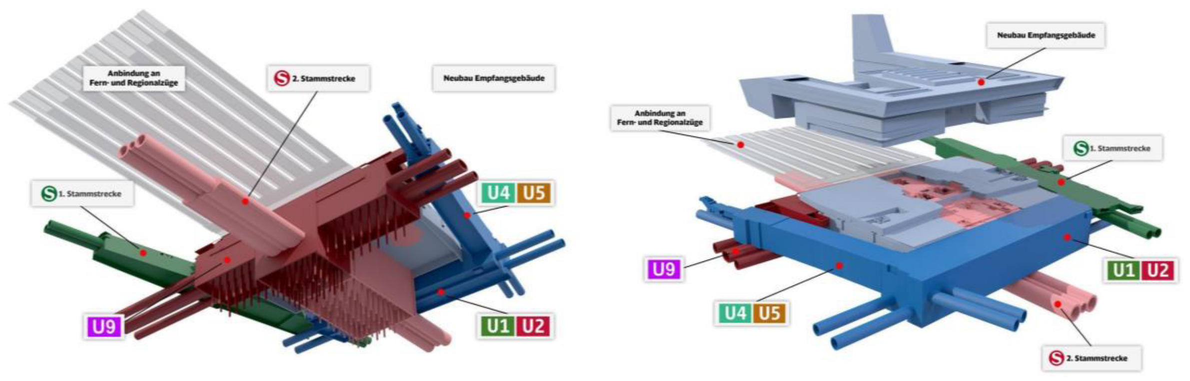

Figure 4: Visualization of Munich Main Station (left: underground system, right: overground buildings) (DB Netz, n.d.-c)

The owner's project team is currently organized based on a matrix structure with a cross-divisional project management level. The project delivery system is design–bid–build (DBB) with some early contractor involvement. Due to many interfaces, limited laydown and construction areas, many different design stages, and different financial funds, considerations were made that IPD could be the best way to deliver the project and achieve the overall goal of finishing the project on time. In addition, the project lead initially thought that IPD could help to reduce the interfaces and support communication across organizational borders operating as an aligned team. This should also help to handle change orders more quickly without the installation of a big claim management process and instead focus on finding solutions through innovation. At all times, the team was aware that due to the constraints imposed by public procurement law, it might be with great difficulty that the procurement process can be designed to include IPD with all its key features (multiparty agreement, modified reimbursement, an incentive system, a modified distribution of liabilities, modified risk allocation, etc.). However, there was a consensus that the greater effort involved in preparing and coordinating the procurement process is far outweighed by the benefits of a subsequently reduced effort for the management of contractors' claims and all the negative implications that come along with it.

In order to change the project delivery system to IPD, the team must analyze and define the scope of the multiparty agreement and be able to communicate the advantages of starting an IPD pilot project to the management board of Deutsche Bahn (DB).

DECISION QUESTIONS

The decision-making questions must be defined to decide if IPD should be applied to the projects. Based on a quick brainstorming, the team identified two questions:

- Q1: Should the project be delivered with DBB or IPD?
- Q2: Which work scope should be part of the IPD (multiparty agreement)?

Workshops were conducted using the CBA tabular method to answer the decision questions. If the decision outcome of the first question was not to do IPD and stay with DBB, then there would be no need for the second question. The second question focused on the scope of the IPD implementation.

OVERVIEW OF THE CBA WORKSHOPS

The workshops were executed with paper and post-its to drive the discussion among the participants and make the process as easy as possible, as it was the first time for the whole group to use CBA (see Schöttle et al., 2022). Before starting with the decisions, the team was introduced to CBA via a presentation and brief examples. During the first workshop, a core group started to prepare the decision for the second workshop, which would have an extended group. Table 1 gives an overview of workshop execution and the progress the team made during the workshop.

Table 1: Overview of Workshop Execution

Workshop Date & Duration	Participants (incl. trainer)	Content
1 (10/06/2022) 3.0 hours	5 (A, B, C, D, E)	• Short introduction to CBA • Defining the decision steps based on questions • Defining factors, criteria, attributes, and advantages for Q1
2 (10/12/2022) 9.5 hours	8 (A, B, C, D, E, F, G, H)	• Building knowledge regarding CBA • Developing a common understanding regarding IPD • Identifying road stoppers for IPD • Clarifying the decision questions and the current organizational setting • Adjusting factors and criteria for Q1 • Defining attributes and advantages for Q1 • Identifying the Paramount Advantage (PA) and sequencing the importance of the highest advantages of every factor
3 (11/14/2022) 3.0 hours	6 (A, B, C, D, E, H)	• Defining the importance of advantages for Q1 • Writing down the argumentation • Defining the alternatives for Q2
4 (11/28/2022) 2.0 hours	4 (A, B, C, H, I)	• Defining factors, criteria, and attributes for Q2
5 (12/05/2022) 2.0 hours	3 (A, B, C, I)	• Determining the advantages for Q2 • Defining the importance for Q2
6 (01/26/2023) 1.0 hour	7 (B, C, D, F, J)	• Presenting the outcome of the tabular method • Reflecting on the tabular • Making the final decision

ANSWERING QUESTION 1

The alternatives DBB to IPD were compared to answer the decision question based on the project context. The factors and criteria were quickly set up using the nominal group technique. The attributes were described, and the advantages were defined (see Figure 5). During the reflection of the defined advantages, the team recognized that there were four factors that were already included in other factors, and thus, decided to eliminate these factors from the CBA tabular. Answering the first question was important for the team to create awareness regarding the difference between DBB (scores of 240) and IPD (scores of 600) and to create a common understanding of IPD. Furthermore, the team identified challenges that need to be considered: (1) convincing stakeholders to do IPD, (2) financing rules based on the different funding, and (3) influences of public procurement law that can impede the successful awarding of contracts containing (key) components of IPD (incentive system, modified risk-allocation, a modified distribution of liabilities, inspection and notification requirements, etc.). Based on the decision outcome (see Figure 6) of the table, the team formulated their argumentation for IPD based on the tabular:

- Significantly higher joint identification with the project goal due to a multiparty contract and the joint definition of the project goals and team goals
- Significantly higher reliability to achieve milestones due to shared goals, transparency, and shared responsibility
- Better decision-making based on the early integration of project participants and their knowledge
- Higher willingness to innovate due to diverse perspectives on a problem
- The complexity of the claim management decreases significantly due to the jointly agreed target costs
- Mutual consideration leads to a higher execution quality due to the overall project view.

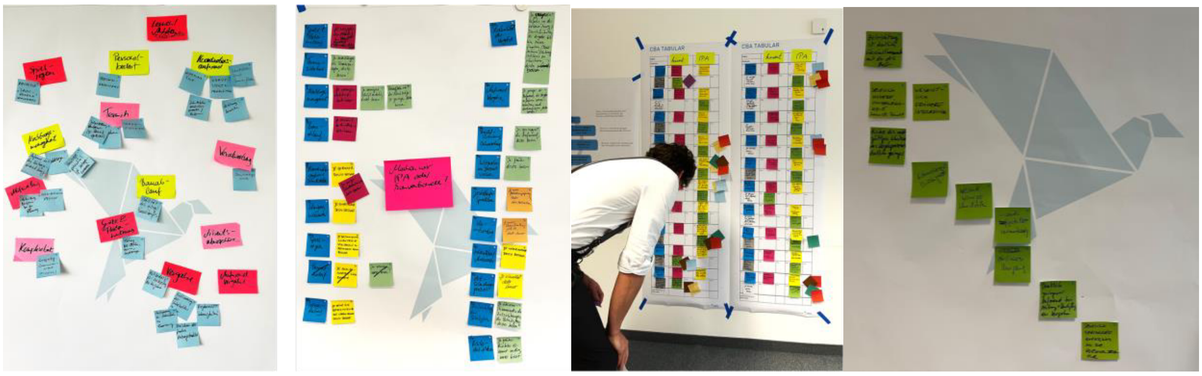

Figure 5: Progress of Workshops 1 and 2 to Answer Q1

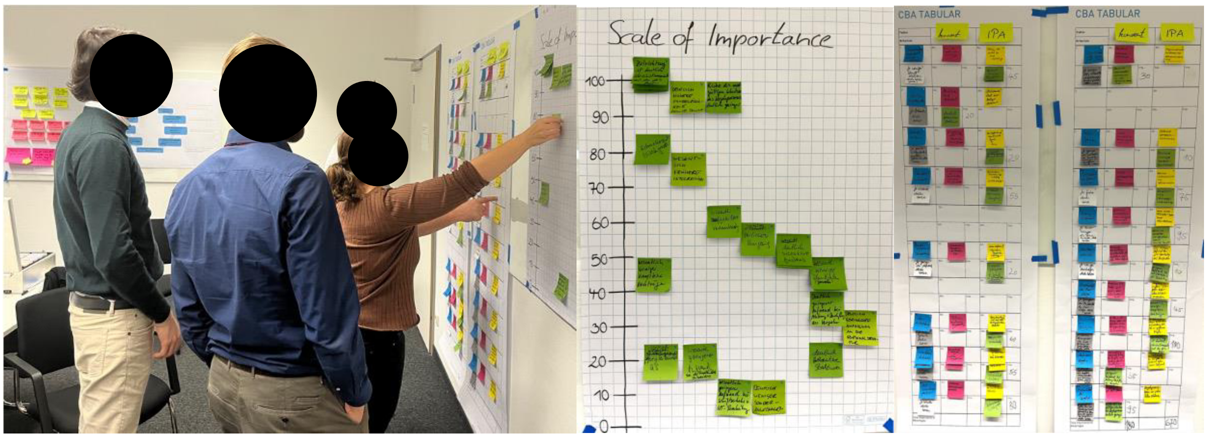

Figure 6: Progress of Workshop 3 to Answer Q1

Answering Question 2

The second question consisted of five alternatives that were identified based on the work scope:

- Alternative 1: Civil engineering underground
- Alternative 2: Civil engineering underground plus building construction (overground)
- Alternative 3: Technical building equipment and interior for over- and underground
- Alternative 4: Building construction (overground) plus technical building equipment and interior for over- and underground
- Alternative 5: Civil engineering underground plus building construction (overground) plus technical building equipment and interior for over- and underground

As the team understood the method better, the second table was quickly set up, and the importance of advantages was assigned (see Figure 7). For better communication, the table was transferred into an Excel spreadsheet to present at the final meeting. Figure 8 shows the completed tabular.

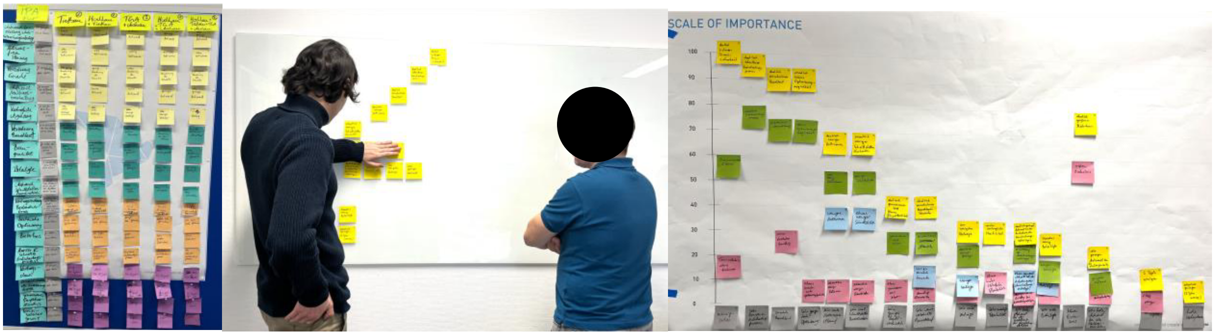

Figure 7: Progress of Workshops 4 and 5 to Answer Q2

Factor / Criteria	Alternative 1: Civil engineering underground		Alternative 2: Civil engineering underground plus building construction (overground)		Alternative 3: Technical building equipment and interior for over- and underground		Alternative 4: Building construction (overground) plus technical building equipment and interior for over- and underground		Alternative 5: Civil engineering underground plus building construction (overground) plus technical building equipment and interior for over- and underground	
Effort for the preparation of tender documents	Very significant effort		Significant effort		Average effort		Low time and effort		Low time and effort	
Less effort for preparation is better.			Insignificantly low time and effort in the preparation of tender documents	5	Somewhat low time and effort in the preparation of tender documents	10	Insignificantly low time and effort in the preparation of tender documents	25	Significantly low time and effort in the preparation of tender documents	30
Collision-free planning	Lots of collisions		Very many collisions		Few collisions		Minimal collisions		No collisions	
Fewer collisions is better.			Imperceptibly fewer collisions	5	Fewer collisions	35	Few collisions	50	Significantly fewer collisions	65
Interlocking of trades	Very little interlocking of the disciplines		Lower interlocking of the disciplines		Average interlocking of the disciplines		High interlocking of the disciplines		Maximum interlocking of the disciplines	
The more interlocked the trades, the better.			Somewhat more interlocked trades	5	Less interlocked trades	10	More interlocked trades	25	Significantly more interlocked trades	40
Time and effort for supplementary processing	Very significant time and effort		Significant time and effort		Significant time and effort		Low time and effort		Low time and effort	
Less is better.			Less time and effort in the subsequent processing		Less time and effort in the subsequent processing	5	Less time and effort in the subsequent processing	10	Very low time and effort in the subsequent processing	20
Contractual delimitation	Very many contracts		Many contracts		Few contracts		Very few contracts		Practically a contract	
The less contracts, the better.			Insignificantly fewer contracts	5	Fewer contracts	10	Significantly fewer contracts	20	The least contracts	30
Interlocking construction process	Very minimal interlocked construction process		Little interlocked construction process		Little interlocked construction process		Moderately interlocked construction process		Completely interlocked construction process	
The more interlocked the construction process, the better.			Somewhat interlocked construction process	25	Somewhat interlocked construction process	25	More interlocked construction process	70	Significantly more interlocked construction process	90
Participants	Very many participants		Many participants		Moderate number of participants		A low number of participants		Very few participants	
The less participants, the better.			imperceptibly fewer participants	5	Slightly fewer participants	10	fewer participants	15	Particularly few participants	25
Time and effort for interface coordination	Very many interfaces		many interfaces		A moderate number of interfaces		Few interfaces		Very few interfaces	
The less interface coordination, the less time and effort, and the better.			Imperceptibly less interface coordination	5	Slightly less interface coordination	35	Less interface coordination	50	Significantly less interface coordination	65
Contract change of existing contracts	Change in civil engineering (moderate flexibility)		Change in civil engineering (moderate flexibility)		Change technical building equipment + interior (low flexibility)		Change technical building equipment + interior (low flexibility)		Change civil engineering + technical building equipment + interior (very low flexibility)	
The greater the contractual flexibility, the better.	More contractual flexibility	30	More contractual flexibility	30	Somewhat more contractual flexibility	10	Somewhat more contractual flexibility	10		
Technical optimization potential	Very low technical optimization		Low technical optimization		Very low technical optimization		High technical optimization		Very high technical optimization	
More optimization potential is better.			A litte bit more optimization potential	5			Higher optimization potential	70	Much higher optimization potential	90
Number of bidders	Very large group of bidders		Very large group of bidders		Large group of bidders		Very large group of bidders		Small group of bidders	
The more bidders, the better.	Significantly larger group of bidders	75	Significantly larger group of bidders	75	Larger group of bidders	55	Significantly larger group of bidders	75		
Fast decision-making process	Very slow decision-making process		Very slow decision-making process		Fast decision making process		Fast decision making process		Very quick decision making process	
The faster, the better.					Quicker decision-making process	75	Quicker decision-making process	75	Significantly faster decision-making process	95
Contract duration	Short contract duration (approx. 6 years)		Long contract duration (approx. 11 years)		Long contract duration (approx. 10 years)		Long contract duration (approx. 10 years)		Long contract duration (approx. 12 years)	
The less, the better.	Significantly less (6 years less)	5								
Interconnection of the financing pots	2 pots (U9 + UG)		3 pots (U9 + UG + building construction)		3 pots (UG + building construction + XXX)		3 pots (UG + building construction + XXX)		4 pots (U9 + UG + building construction + XXX)	
The less pots, the better.	2 pots less	15	1 pot less	5	1 pot less	5	1 pot less	5		
A common understanding of the project	Very low understanding of the project		low		low		A high understanding of the project		A very high understanding of the project	
The more common and clearer, the better.			Somewhat more common and clearer	5	Somewhat more common and clearer	5	More common and clearer	25	Significantly more common and clearer	40
Total scheduling security	Not very safe		Secure		Somewhat secure		Secure		Very secure	
The more secure, the better.			More scheduling security	55	Scheduling security somewhat more secure	15	More scheduling security	55	Significantly safer scheduling security	100
Total importance of advantages		125		230		305		580		690

Factor / Criteria	Alternative 1:		Alternative 2:		Alternative 3:		Alternative 4:		Alternative 5:	
Number of bidders	Very large group of bidders		Very large group of bidders		Large group of bidders		Very large group of bidders		Small group of bidders	
The more bidders, the better.	Significantly larger group of bidders	75	Significantly larger group of bidders	75	Larger group of bidders	55	Significantly larger group of bidders	75		
Fast decision-making process	Very slow decision-making process		Very slow decision-making process		Fast decision making process		Fast decision making process		Very quick decision making process	
The faster, the better.					Quicker decision-making process	75	Quicker decision-making process	75	Significantly faster decision-making process	95
Contract duration	Short contract duration (approx. 6 years)		Long contract duration (approx. 11 years)		Long contract duration (approx. 10 years)		Long contract duration (approx. 10 years)		Long contract duration (approx. 12 years)	
The less, the better.	Significantly less (6 years less)	5								

Figure 8: CBA Tabular for Q2 and Exemplary Extract

The most important advantages of the decision were significantly higher schedule reliability, the advantage of much faster decision-making, the advantage of having significantly higher technical optimization possibilities, and the advantage of a significantly more integrated/interlinked construction process.

On January 26, 2023, the team came together to reflect on the tabular to finalize the decision. By doing so, they recognized that a certain condition needed to be considered. As the second city train line is connected to the main station, the underground works of the main station have to reach a certain point in their structural work so that the schedule of start-up and commissioning of the second line can be achieved. Thus, the civil engineering of the underground needs to be executed as quickly as possible and cannot wait for the delivery system change as this could result in a delay in the completion of the 2.SBSS. This risk must be mitigated by proceeding with the structural underground work as soon as possible, resulting in exclusion from the IPD scope. As the technical building equipment must work as one system for underground and overground and because there is enough time between the start of installation and changing the delivery system, the equipment for the overground buildings, as well as the underground buildings, will be included in the IPD to avoid producing a big interface. Therefore, although alternative 5 (score of 690) achieved the highest overall importance of advantages, the team decided to apply alternative 4 (score of 580) due to the strategic consideration on start-up and commissioning.

The next step in moving forward with the IPD approach is a conceptual presentation by the final decision-making team outside the project team, as this will be an outstanding pilot project for the DB. Furthermore, the funding stakeholders, the city of Munich, the Free State Bavaria, and the federal government must agree too.

FINDINGS FROM DATA COLLECTION

FINDINGS FROM SURVEY

General questions regarding strategic decision-making

To better understand the baseline, the survey participants were first asked why the preparation of the decision was important. Paraphrasing, the following answers were given: (1) Setting the strategic direction/structuring the overall project and the procurement process, (2) transparent/comprehensible documentation of the decision and the decision-making process, (3) argumentation support/decision preparation for the approval process, (4) determination of synergies and potential savings, (5) collaborative, objective, and fast-track decision-making. Participants were then asked what it takes to push through and communicate such a strategic decision. The answers can be clustered into four factors: **(1) Conviction**—vision, courage, confidence, will of everyone, interest in doing something new, keeping focus in the event of backlash, political openness, discourse with IPD, collaborative mindset, consent of those involved, and convincing important stakeholders. **(2) Unity**—close coordination with the procurement and legal department, strong network within the company's management level, and secured financial funding. **(3) Knowledge**—knowledge-building CBA and IPD at a very high decision-making level, basic knowledge of all project phases and trades, and experience in megaprojects. **(4) Documentation and communication**—considering the different perspectives, good preparation, structured way, traceability of decision, informative presentation (including risks and opportunities)/reasoning of the benefits and explaining the why.

Questions regarding workshops

Participants were asked if the application of CBA helped to reason the change of the project delivery system. Seven of the participants said yes, and one participant (I) said no. The negative response could be an indicator of lack of training as the participant missed the first workshops, which set the basis and gave clarity regarding the process.

Retrospectively, the participants observed that the team made the decision together and achieved fast consensus by discussing different interests openly and honestly. Working with the tabular created information symmetry easily, although it showed the complexity of the decision. Moreover, one participant responded that factors were considered that would not have arisen in classic decision-making. The method promotes the consideration of different perspectives and therefore represents the multitude of topics and different interests of the project. Nevertheless, due to the lack of consistent participation and the degree of involvement, the decision result might include a bias due to the assignment of importance (scoring). One participant reflected that the result was not fully objective. This response aligns with previous findings that decisions always contain subjectivity by nature (Schöttle et al., 2020; Suhr, 1999).

In summary, participants answered that CBA helped to communicate and enforce the decision within the project team to onboard stakeholders and achieve commitment to proceed with the decision. As participant (J) stated, "Involving a large number of people in the discussion is exhausting, but necessary and faster in the end since everyone is involved, and all issues are directly discussed."

FINDINGS FROM SHORT INTERVIEWS

During the short interview, participant (J) said that the tabular structures all relevant aspects. Participant (F) mentioned in his interview that the tabular was very comprehensible and contained more aspects than he anticipated. Furthermore, participant (F) stated that the degree of detail was more than he expected and that the detailed analysis of the alternatives helped to understand the decision resulting in confidence and reliability regarding the outcome. Participants (F) and (J) observed that the team stood behind the outcome and showed confidence, as different perspectives were integrated through the process, and the team worked together on the decision. Thus, stakeholders that were not involved in the decision-making process and stakeholders that might be joining the project can understand why the delivery system must change to IPD without asking the same questions that came up during the workshop. This is an important indicator for the project lead that they developed a stable and comprehensible argumentation as stakeholders outside the project need to give their approval.

Participant (J) stated: "CBA fits great with IPD because decisions can't be made in the same manner as before. [...] We need to make decisions collaboratively to include different perspectives." The findings also show that the team already has a collaborative mindset necessary for the change. As the owner knows, the lack of experience on all ends in the owners, architects, engineers, and contractors (OAEC) industry in Germany regarding IPD will require a joint learning process from all stakeholders.

DISCUSSION AND CONCLUSION

The process created clarity regarding the alternatives that should be considered in the decision-making process. The process showed the team which advantages are more important and which differences between alternatives are less relevant to the decision. Moreover, the tabular gives a clear overview of where the highest importance of advantages is located so that the team was able to make a sound decision. As the difference between alternatives 4 and 5 of the second question was not as big as the other alternatives (Alternative 1: 125 scores, Alternative 2: 230 scores, Alternative 3: 350 scores, Alternative 4: 580 scores, Alternative 5: 690 scores), the team was questioning whether to go with alternatives 4 or 5 by taking certain conditions into account.

Furthermore, the transparent and easily understandable documentation helped them to communicate the decision outcome. For example, seeing the CBA tabular for the first time at the final meeting and without any knowledge regarding CBA, the fourth author was able to understand the tabular but needed to get a further explanation about the way the scores were assigned. Using the method the first time, the second author (B) was able to present the tabular and answered questions regarding the procedure to the group. This shows that with an open mindset, training, and a coach guiding the team to use the method correctly, CBA can be easily learned, and although CBA was new to the team, the time spent working on the decision was short. Thus, it was important that a facilitator guided the team through the process and helped participants to voice their thoughts.

Based on the presented case, it can be stated that the CBA tabular method helped to (1) create a shared understanding of IPD, (2) understand which scope should be part of the multiparty agreement, (3) organize the argumentation, and (4) create trust regarding the argumentation. In this context, the CBA tabular method was not only used to make the decision but was also used to create a common understanding of IPD and the difference between IPD and DBB. Within a short time, the team was able to share their understanding regarding IPD and discuss the consequences of the system change. Moreover, determining the advantages showed the team the differences regarding the work scope that should be part of the multiparty agreement and supported the identification of constraints that the team was not aware of from the beginning. CBA is an enabler for conversations in a structured and productive way while focusing on the relevant facts. In doing so, CBA helped to reason the change in the delivery system.

ACKNOWLEDGMENTS

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CAPABILITY-BUILDING FOR CONSTRUCTION INFORMING DESIGN

Dean Reed[1], Chad Arthur[2], and Charlie Dunn[3]

ABSTRACT

The research question is whether Takahiro Fujimoto's theory of capability-building to create the Toyota Production System (TPS) is useful to understand the creation of a capability for Construction knowledge to inform design (CID). This paper attempts to reveal what was done in sufficient detail to compare it against Fujimoto's explanation of how Toyota's capability-building created TPS. The method used was to create and analyze data using the Fujimoto framework explained in his book, *The Evolution of a Manufacturing System at Toyota*. Fujimoto's theory allowed the authors to confirm that Toyota-style capability was created and delivered a significant competitive advantage in 2 of 4 projects where CID was attempted. The capability was created without knowledge of Fujimoto's theory of Toyota's capability-building. As with previous studies, it was impossible to identify routines developed to implement the process steps. It was also not possible to distinguish process steps for learning from others for production. Industry fragmentation is an obstacle to the level of integration this capability requires of designers and builders. The capability for construction knowledge to inform design can be created and requires vision and leadership to challenge the traditional design process.

KEYWORDS

Theory, capability, autoethnography, emergence, evolutionary.

INTRODUCTION

This paper is autoethnographic research about building capability to solve the problem of late and insufficient construction knowledge to inform design as it develops, especially early. The first author is the ethnographer, and the second author is the participant entrepreneur, designer, and manager of the capability-building, reflecting on his experiences to report what transpired. The third author, another ethnographer, has prior experience with this specific capability-building in the nuclear industry, but for this paper has focused primarily on the communication strategy and next steps for the general construction industry. Although conceived to test through Action Research, the research methodology is a variant of autoethnography, specifically "layered accounts," which is "author's experience alongside data and abstract analysis, and relevant literature." (Ellis et al. 2011) The research is post hoc looking back on experience considering a method that was not known to participants at the time.

The purpose of the research is to determine whether and how Takahiro Fujimoto's explanation of how Toyota continually improved is useful for leaders trying to do that within Construction. The real-world problem is the architects and engineers design without builders'

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knowledge of construction constraints. The supply chain requires design intent before builders, fabricators, and product suppliers are procured, which limits the possibility of using Design for Manufacture and Assembly (DfMA) principles (Pasquire and Connolly 2003). Currently, design is conveyed through documents without a rigorous constructability review, leaving the Request for Information (RFI) process as the only mechanism for the general and trade contractors to call attention to problems and offer solutions. BIM clash detection is then started without alignment between design/engineering, and fabrication and assembly information. Preferred building methods, especially prefabrication, are not reflected in the design and the opportunity for design innovation that would create cost and schedule savings is lost.

The second author realized this several years ago while working as a designer on a Design-Build project and decided that he wasn't going to detail solutions that would become obsolete once the build partner was brought on board. He decided to focus on conveying design intent between systems and allowed the trades' subject matter experts to help drive overall constraints of the building systems and provide details that they could build, creating cost savings and innovations in overall design of the building.

After joining a large U.S. General Contractor (GC) as a Virtual Design and Construction (VDC) specialist, the second author, the "protagonist" in this story, was asked to assist a Design-Build student housing project team implementing a prefabricated structural cold-formed steel stud wall panel and flooring system in which the GC team was committed to informing the design team about constraints in the prefabrication process. The dormitories were very repetitive, so the protagonist selected a corner of one of the middle floors and set some clear objectives to work through for 6 weeks, including: trade partners preferred details, and the coordination of a detailed model in that strategic location. The decisions made during this process were then scaled across the project in early design phases. During this work he created templates to use across the GC's multiple offices throughout the country. Figure 1 shows this process.

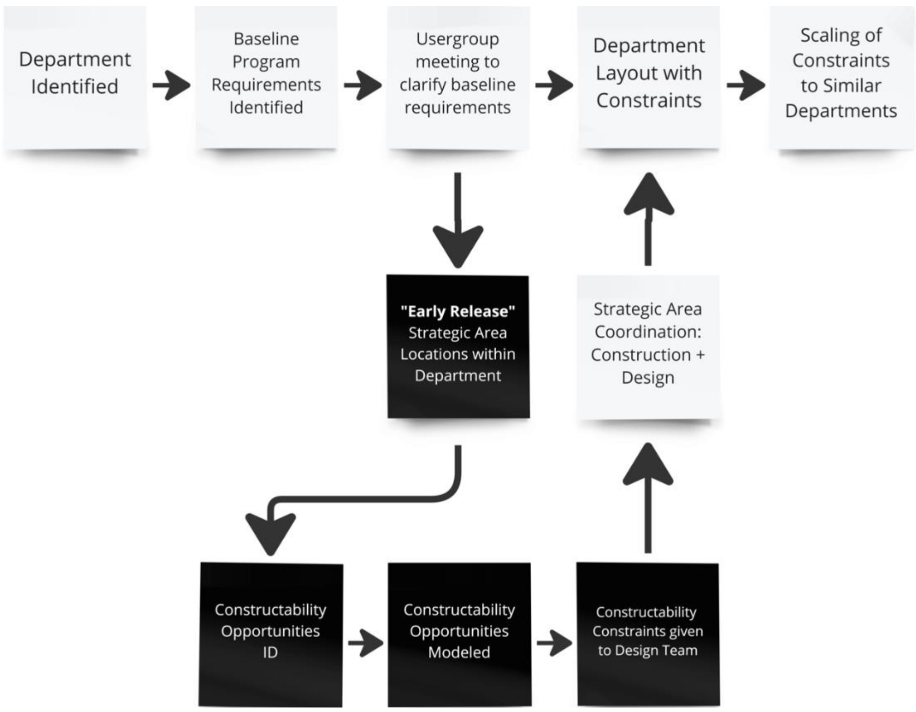

Figure 1: Typical Construction Informing Design Workflow

This typical workflow for Construction Informing Design is intended to be repeated through multiple typologies that exist in a project. Incrementally releasing functional program for strategic in-depth analysis creates the opportunity for programming, conceptual design, and constructability to happen concurrently. Key release points at user group review meetings and initial department layouts, as depicted in Figure 1, are critical to the success of this process and trigger key consolidation points to incorporate constructability constraints into the design.

Based on this experience, the authors decided to research whether and to what extent Takahiro's explanation of Toyota capability-building could explain what transpired on the 4 projects on which the second author organized project teams to enable Construction to Inform Design. This paper is an attempt to answer that question.

LITERATURE REVIEW

The only reference to Fujimoto the first author found prior to initiating a prior study reported in a 2019 IGLC paper was in a 2001 IGLC paper titled "System View of Lean Construction Application Opportunities" by Flavio Picchi (2001). He noted Fujimoto's evolutionary perspective starting from 3 levels of manufacturing capability anchored in routines for manufacturing, learning, and developing new capabilities by combining ones already developed. Niklas Modig and Par Ahlstrom also mention these 3 types of Toyota capability in their book, *This Is Lean* (Modig and Åhlström 2012), and point to Fujimoto's explanation of how the Toyota Production System emerged through trial-and-error capability-building. Their praise led the first author to read Fujimoto' book, *Competing to Be, Really Really Good* (Fujimoto and Miller 2007), followed by *The Birth of Lean* (Shimokawa and Takahiro Fujimoto 2009), a compilation of interviews with men who worked alongside plant manager Taicihi Ohno, and finally *The Evolution of a Manufacturing System at Toyota* (Takahiro Fujimoto 1999), all of which are essential to undertake researching Toyota-style capability-building. However important these are, the first author needed Mike Rother's explanation of Toyota's improvement and coaching practices, "katas," (Rother 2010) to develop the research methodology used in this and 3 previous IGLC papers. (Berg and Reed 2019) (Berg et al. 2020) (Reed et al. 2021)

THEORETICAL FRAMEWORK

This research uses Fujimoto's definition of organizational capability as the power or ability of an organized group to do something using effective routines. Our work is based on Fujimoto's explanation of how and why Toyota's capability to build capability led to the Toyota Production System (TPS). He begins by explaining that the purpose of building capability for Toyota and other automakers is to become more competitive in the marketplace by solving potential customers' problems better than competitors. According to Fujimoto, the starting point for understanding capability-building is the process steps that become routines for coordination, developing information, or fabricating and/or installing components and assemblies to improve production, and learning to improve processes.

Fujimoto identifies 3 levels of manufacturing capability as follows:

1. Routinized Manufacturing Capability. Its produces competitive performance in a stable environment where necessary prerequisites flow and the product can be made predictably. Its primary characteristics are a firm or project-specific pattern of steady-state and efficient transfer of accurate information.
2. Routinized Learning Capability. It allows for changes or recoveries of competitive performance in a dynamic environment. Its primary characteristics are a firm or project-specific ability of handling repetitive problem-solving cycles or an expected pattern of system changes.
3. Evolutionary Learning Capability. It enables changes in patterns of routines that contribute to capability. Its primary characteristic is the ability of handling system

emergence, i.e., dealing with non-routine patterns of system changes to form new routine capabilities.

TPS-style process steps are comprised of actions that can be measured or assessed against a desired outcome by the people who perform them, which enable learning and improvement. Routines can be effective for safety, quality, accuracy, and production goals, so it's important and often imperative that these adhere to guidelines that allow for inherent human differences. People must be encouraged and rewarded to continually improve these "best practices" as well as to invent better ways to do their work. The role of managers is to ensure that the people who perform the work are provided the training, information, and tools they need in the safest possible environment. The why loop must be closed by managers and performers through assessing whether the capability is achieving the success criteria established as targets. "The Toyota Way" is for people to strive to reach a future state by working towards intermediate target conditions (Rother 2010). This is the engine of continuous improvement.

Fujimoto identified 5 pathways for solving problems, as follows.

1. Rational Calculation: classic product design problem-solving.
2. Environmental Constraints: circumstances negating a usually viable solution.
3. Entrepreneurial Vision: pursuing solutions advocated by leaders.
4. Knowledge Transfer: following the advice of experts within or outside the project.
5. Random Trials: testing a variety of possible solutions.

Fujimoto also defined 4 ascending levels of capability-building within Toyota. The first is system change, activities that lead to change within the system to which a capability contributes. The second level is "Multi-Path System Emergence" when a variety of patterns (sequence and arrangement) in system changes can be seen in combination without a clear relationship between the pattern and content of system changes. Multi-Path System Emergence coupled with routinized capability indicates the capability to build new capability, which Fujimoto named "Evolutionary Learning Capability." As noted above, Fujimoto also defined this as the third level of manufacturing capability, and the key to Toyota's success. Fujimoto identified a fourth, penultimate level of capability-building, which he called "Dual-Layer Problem-Solving." This is when Multi-Path System Emergence and Evolutionary Learning give leaders the opportunity to create new solutions at a higher organization level based on solutions emerging from lower lever problem solving (Takahiro Fujimoto 1999).

RESEARCH METHOD

The method incorporates steps that were not explained by Fujimoto and are necessary to execute TPS capability-building to improve competitiveness in the marketplace. All would be used in Action Research and were used in this autoethnographic research, based on reflection.

The first author asked the questions based on his understanding of Fujimoto's explanation of how Toyota's capability-building led to TPS. The second author, who designated the objectives and process for achieving them and taught these to new members of each of 4 project teams, answered the questions. Reporting on what was done and accomplished for this study, he was able to draw upon project information such Building Information Models, work plans, meeting agendas and minutes, correspondence, schedules, budget, and cost reports. He also kept and could refer to extensive personal notes to answer questions based on the research method described above.

INFORMATION REQUESTED FROM THE PARTICIPANT AUTHOR

1. Identify projects attempting to build and implement the capability.

2. Articulate the “Direction or Challenge” (Toyota Improvement Kata step 1) stated as the purpose.
3. Define the “Current Condition” (Toyota Improvement Kata step 2).
4. Establish the "Next Target Condition” objective, which are the “Competitive Success Criteria” for the capability (Toyota Improvement Kata step 3). (Rother 2010)
5. Identify key people contributing to the new capability and describe their roles.
6. Define the process developed collaboratively with the team by describing each step to achieve the Next Target Condition including the next customer for the step, responsibility, frequency, time span, and expected results.
7. Evaluate “Routinized Capability,” the use of process steps by determining the extent each step was used on a 1-5 Likert Scale, step used as intended: 5, strongly agree; 4, agree; 3, neither agree nor disagree; 2, disagree; 1, strongly disagree.
8. Evaluate Competitiveness by assessing the impact of all capability process steps considered together on each of the competitive criteria with each success criteria contributing an equal percentage to the total competitiveness score for the capability on the same 1-5 Likert Scale.
9. Determine “Effective Use.” This requires both routinized capability (the sum of steps used equal to or greater than 75%) and “Capability Competitiveness” (capability improvement equal to or greater than 75%) This is outside the Fujimoto framework, done to see the relationship of routinized capability and competitiveness.
10. Identify “Problem-Solving Paths” by answering yes or no to whether each of which the 5 paths to solving problems described by Fujimoto contributed to the capability.
11. Determine “System Change Impact” for only the projects having Routinized Capability by answering yes or no to whether there were changes in the system/subsystem to which the capability contributed, in this case “Constructable Design Development Documents within Allowable Cost.”
12. Determine “Multi-Path System Emergence” for only those projects with System Change Impact by first answering yes or no to whether there were variety of patterns (sequence and arrangement) in system changes; and second by answering yes or no to whether a clear relationship between the pattern and content of system changes could be seen. If there was no relationship between pattern and content, there is Multi-Path System Emergence.
13. Determine Evolutionary Learning Capability by answering yes or no to whether Routinized Capability and Multi-Path System Emergence were present.
14. Determine Dual Layer Problem Solving, separate from and regardless of whether there is Evolutionary Learning Capability, by answering yes or no to whether intentional selection and modification of capability solutions to produce new capability to solve other problems could be seen.

DATA

The second author reported the following.

1. Direction/Challenge. CID purpose is for Construction subject matter experts (SMEs) to proactively provide constructability information for building systems and components including procurement lead times, installation durations, cost and schedule impacts, prefabrication possibilities, and BIM details to architects and engineers according to mutually agreed dates in formats that can used to develop construction documents.
2. Current Condition. Architects and engineers design without builders’ knowledge of construction constraints.

3. Next Target Condition success criteria stated as objectives are as follows.
    a. First, no unplanned negative iteration in the design process.
    b. Second, content provided by design team has been reviewed and signed off by project member companies responsible for putting the work in place.
    c. Third, design intent dimensioning is in alignment with construction detailing.
    d. Fourth, prefabrication opportunities are incorporated into the construction documents.
4. Key contributors to the capability are as follows.
    a. Preconstruction Manager (PCM). Procurement and financial setup to allow trade partners to engage in the early phases of design. Setup of project estimates to capture strategic deep dive information that will inform overall costs.
    b. Design Manager (DM). Packaging and alignment of client information, designer content, and contractor provided content. Leads early alignment session on timing and overall objectives for the process. Provides example content for similar proposed solutions or leads charrettes to gain team alignment.
    c. Superintendent (SI). Identifies locations in the project or specific program scope that will inform the overall schedule and logistics plan. Sets goals for flow of work and prefabrication approaches that will impact design.
    d. VDC Manager or Senior Engineer (VDC). Sets up the model environment and clearly conveys to the extended team where they should focus in the 3D environment. Creates 3D views and sheets to capture design decisions as they are made and tracks actions in a single location for the team to update in the model.
5. Process steps, responsibilities and Next Target Condition success criteria for projects are shown in Table 2.
6. Table 1 describes the projects on which teams attempted to build and implement the capability and summarizes what transpired.
7. Routinized Capability, the use of process steps, is shown in Table 2 for each the 4 projects studied. Use of process steps reached the 75% threshold for only the first 2 projects.
8. Next Target Condition Competitiveness scores are also shown in Table 2. Three of the 4 CID capability projects substantially improved competitiveness.
9. Effective Use scores are also reported in Table 2.
10. Problem-Solving Paths. All 4 project teams employed 3 of the 5 problems-solving paths identified by Fujimoto: Rational Calculation, Entrepreneurial Vision, and Knowledge Transfer. Environmental Constraints and Random Trials were not used.
11. System Change Impact. The Constructable Design Development Documents within Allowable Cost subsystem, which the CID capability supported, was changed, and improved in the first 2 projects, the ones with Effective Use (high use and competitive scores), but not in the other 2 where it was not achieved.
12. Multi-Path System Emergence. Both projects with System Change Impact displayed a clear relationship between the pattern and content of system changes. Since Emergence is indicated by no clear relationship between the content and pattern of changes, neither could be said to have it.
13. Evolutionary Learning Capability requires Routinize Capability and Multi-Path System Emergence. None of the projects achieved this.
14. Dual Layer Problem Solving. Intentional selection and modification of capability solutions to produce new capability to solve other problems was not visible in any of the projects.

Table 1: Capability Application on Projects

#	Descr	What Worked	Contract Type	Integration
1	Higher Education Student Housing	Builder details incorporated into overall design intent of the project.	Design-Build Guaranteed Maximum Price	The architect and extended team were fully committed to the process.
2	Higher Education Teaching and Learning	Alignment with principal designer early on intent. Trade coordination and Construction Document level information was produced out of the process to inform design.	Design-Build Guaranteed Maximum Price	The team would have liked to continue the process once they were done with the first strategic location was complete on the project.
3	Corporate Office	Detailed trade models quickly identified dozens of design issues and potential design solutions.	Construction Manager at Risk	The architect stopped the process after a few weeks and stated it was too early in the process.
4	Higher Education Healthcare Provider	Alignment with cost program modelling process helped identify building and area specific variables. Detailed pull plans for key work informed overall pull planning activities.	Design-Build Guaranteed Maximum Price	Multiple pauses due to the overall project deadlines and concurrent incremental packages.

Table 2: Use of Process Steps

Step	Description	Who	Prj.1	Prj.2	Prj.3	Prj.4
1	Early alignment with project leadership on approach and execution	DM	5	5	2	4
2	Early alignment on timing of process to inform procurement strategy	PM	5	5	1	3
3	Stakeholders are identified and procured for the duration of the activity	PM	4	5	2	3
4	Extended team alignment on benefit and approach	DM	5	5	2	3
5	Clear program and building areas are defined and known information for the given scope is categorized into a single location	DM	5	3	5	3
6	Standard templates and program data are reviewed and agreed upon as a baseline for design intent	DM	4	5	2	4
7	Model is setup and extended team members models are linked in with matching coordinates	VDC	5	5	2	5
8	Boundaries are clearly defined in 3 dimensions	VDC	4	5	5	3
9	Model updates and tasks are tracked in a single location and shared with the extended team	VDC	4	5	3	1

Table 3: Projects Process Steps Use Summary (continued)

Step	Description	Who	Prj.1	Prj.2	Prj.3	Prj.4
10	Locations variables are identified and labelled	DM	5	5	5	3
11	Overall building systems impacted in each area are identified and labelled	DM	4	2	5	2
12	Overall duration and cadence are set with clear goals at each cadence interval	DM	5	5	1	3
13	Builder details are proposed, and locations are identified within the defined boundary	DM	4	5	3	4
14	Prefabrication opportunities are proposed and identified within the defined boundary	SI	5	5	1	3
15	Cost impacts are estimated for proposed building systems and compared to industry baselines	PCM	4	4	1	4
16	Schedule impacts are predicted for proposed building systems and compared to industry baselines	SI	5	5	1	4
17	Builder intent is integrated into construction documents, and prefab opportunities are identified and published	DM	5	5	2	4
	Routinized Use Total		78	79	43	56
	Routinized Use Score		92%	93%	51%	66%
	Capability Competitiveness Score		100%	95%	35%	80%
	Effective Use (Use & Competitiveness =>75%)		Yes	Yes	No	No

ANALYSIS

The first author compiled and performed the simple calculations required. Without more data from other projects, no statistical analysis was possible. Proceeding, the authors focused on sense-making and application. Even during information gathering, it was apparent that the questions made sense and were not difficult to answer. This was true of the data; it produced insights that hadn't occurred to the second author. Similarly, the second author realized that the method and findings could be applied to future projects, making it easier for him to explain his approach and describe possible outcomes to project team members.

RESULTS

FINDINGS

All the process steps and resulting work routines contributed to Routinized Learning Capability. None were for Routinized Manufacturing Capability. Three of the 5 pathways were used on all 4 projects: Rational Calculation (classic product design problem-solving), Entrepreneurial Vision, and Knowledge Transfer. This was because the protagonist second author brought all three. The CID capability was used effectively on 2 of the 4 projects evaluated. In the other 2, the architect refused to collaborate on one, and the GC team members responsible for process steps did not execute them well enough on the other. In the 2 projects with Routinized Capability, the Constructable Design Development Documents within Allowable Cost subsystem was created to the benefit of the project. The General Contractor earned high success criteria scores and met their own competitive advantage goals.

The process steps were well conceived, including a very robust use of BIM, information sharing, and collaboration practices. And they could be taught to people willing to learn. Integrating the efforts of participating companies required their project leaders to commit to executing the process steps. While this was done by GC team members on all 4 projects, it succeeded on only 2 because other team members did not participate fully. Multi-Path System Emergence, Evolutionary Learning Capability, and Dual-Layer Problem-Solving were not visible on any of the 4 projects.

LIMITATIONS OF THE RESEARCH

The most significant limitation is that the CID capability was created without awareness of the Fujimoto framework, and the derivative research questions because the second author was not aware of them until he worked on this paper. Had it been otherwise, and Action Research been possible, participants and the researchers may well have learned and accomplished more.

Although Fujimoto speaks of routines, he only describes them at a high level. This is not surprising because that would require near constant attention from an informed manager or observer in the workplace. This is because routines are actions taken by people to execute their responsibilities. There could be just a few or many routines required to complete a process step by an individual or team. Even the second author could not recall and describe routines for action within the process steps. In the experience of the authors, designers and builders rarely define process steps, and even when this is done, transforming them into effective routines is left to individuals. This is why the primary element in this study is process steps. These did not include those for manufacturing, what Construction people think of as off and on-site production and assembly of building elements, so nothing was learned about this critical piece of the capability puzzle.

DISCUSSION

MEANING

Even though it is very different from current practice, CID capability can be created on this GC's projects where the second author is present. As with the 3 other capabilities studied in previous IGLC papers, the CID capability is fragile, meaning that it can be implemented where a protagonist can contribute vision, knowledge, and lead effective problem-solving, i.e., 3 of the 5 problem-solving paths. CID teams that fail to memorialize and communicate durations, the extent of BIM, and tracking progress are not as successful. New competencies such as Virtual Design and Construction and Design Management are required. The Project Superintendent must be involved earlier and to a greater extent than in current practice. Engaged project leadership and team alignment with design team customers is critical for success of CID capability. Cost and schedule metric tracking is yet to be defined and will require additional project team effort as well as greater rigor. The CID capability improved effective use substantially in 2 of the 4 projects, making it worthwhile to improve and implement whenever team members are willing to give it a try.

QUESTIONS THAT COULD NOT BE ANSWERED

How the CID process impacted the design team from their perspective is not addressed in this study. Similarly, the challenges faced by individuals implementing CID is not documented. The biggest question for the authors is how much better outcomes would be in an Action Research implementation with frequent team reflections and problem-solving focused on the process.

IMPLICATIONS

CID capability requires greater collaboration between team members. The fragmentation of design and construction is reflected within contractor organizations and is a barrier to implementing CID. Resources with deep construction knowledge are often not available, or are not encouraged to integrate early, both at the GC and the trade levels. Implementing CID requires people who are open to change and willing to learn, which is difficult without company and project cultures which support working in an integrated way.

CONCLUSION

KNOWLEDGE GAINED BY PARTICIPANTS, AND VALUE FOR PRACTITIONERS

It is both possible and desirable to create CID capability to provide greater value to the Owner. The design team must want early builder constructability input for the CID capability to impact the Constructable Design Development Documents within Allowable Cost subsystem. Without that, CID capability is wasted. Client contracting methods such as IPD and Design-Build are evolving and creating the opportunity for this process to occur. Builders and fabricators can create CID capability, which will extend its impact.

VALUE FOR PRACTITIONERS

The reluctance of the design team in the project where it was not successful was surprising. The traditional design process has been disrupted by the BIM process for years but has still not fundamentally changed how design is done and the cost of projects is predicted. The ability to connect design intent with builder execution is worthwhile because doing so eliminates waste and rework in design while making it possible for project teams to deliver significantly greater value to the customer.

RESEARCH INSIGHTS

The CID process challenges our current contracting method and the silos that exist within the AEC industry. Earlier procurement of trade partners and utilization of 3D collaborative environments make faster design iteration possible, leading to higher levels of cost and schedule certainty.

SPECULATIONS AND QUESTIONS

The authors' intuition is that integrated ecosystems composed of designers, builders and fabricators would want to develop CID capability, and at some point, make it a condition of entry. The capability to model cost at the space program level, studied in a 2020 IGLC paper (Berg et al. 2020) could and should be paired with CID capability. This would make it possible for integrated project teams to consistently capture cost and schedule impacts to feedback for clarification of design intent early in Conceptual Design. A big question is how CID capability can impact procurement and the supply chain to make outcomes more predictable.

FURTHER RESEARCH

Use Action Research to study another set of CID capability projects where the second author is engaged, and another where he is not, and the effort is led by other Design and VDC managers. Extend the CID capability to associate cost and schedule impacts of prefabrication opportunities that can be identified and memorialized earlier using the process. Capture and catalogue rules, constraints and assumptions made through the CID process to inform future projects with similar scopes.

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LEARNING FROM DELAYS IN DAILY DESIGN WORK – COMPARISON OF ROOT CAUSE ANALYSIS AND FUNCTIONAL RESONANCE ANALYSIS

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ABSTRACT

Procurement and construction work depend on error-free and on-time designs. However, the design process may be erroneous and behind schedule, which often causes cascading delays and problems in the construction process. Hence, when a major delay occurs, practitioners often query the design process, and much time and many resources may be required to find the root cause. However, minor delays and mistakes that occur in everyday work are not usually investigated, even though they can contain information necessary to avoid significant adverse events. This study aimed to determine how three deviations that occurred in a normal, well-progressing project can be investigated using two different methods, as well as the significance of small errors and events in preventing larger errors and events in the future. Root cause analysis and functional resonance analysis were the research methods. The findings of this study showed that slight variability in trivial design and design management tasks generated a considerable number of unnecessary tasks and delays. Therefore, examining variability in the outputs of tasks could benefit designers and design management.

KEYWORDS

design, root cause analysis, Ishikawa diagram, functional resonance analysis, FRAM, RCA

INTRODUCTION

A building project consists of a conceptual design, schematic design and detailed design. Each design discipline considers the others' knowledge, processes and solution proposals in meeting the client's needs and requirements (Wang et al., 2014). The daily work of a designer involves a great deal of technical expertise in the field, which includes many different phases of the design process, such as clarifying tasks, searching intuitively for solutions, working through solution principles and concept options and making various qualitative choices (Robinson, 2012). A significant part of the designer's daily work involves non-technical tasks. such as reporting, personal work planning, information retrieval and social interaction (Hales, 1987). However, the multidisciplinary design process is prone to delays, which can also affect the construction process during the detailed design phase (Pikas et al., 2020).

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Design delays have several adverse effects. Delays in design are a significant risk for construction projects, which can lead to extreme changes in the production phase (Mbachu, 2011). Design delays can also affect the work of the project team by reducing trust among the parties involved (Uusitalo et al., 2019). Therefore, design delays in the construction industry have been studied extensively, and efforts have been made to learn from them through both research and practice.

Root cause analysis (RCA) is a common technique used to learn from mistakes. The goal of RCA is to enable individuals to learn from their mistakes and gain a deep understanding of their root causes (RC), thus preventing their recurrence (Cerniglia-Lowensen, 2015). The target of RCA is to repeatedly ask "why" questions to determine the RC and remove it to prevent the harmful event from recurring. This method is often called the five times why (5 x why) method. By asking at least five times in a row about the RC, the most common and intuitive reason often reveals complex and hidden factors related to the occurrence of the event. RCA has become widespread in research and business. One of the earliest developers and users of this method was Professor Kaoru Ishikawa, who introduced RCA in a factory environment in Japan in the 1940s to improve quality (Doggett, 2005). The most typical graphical use of RCA is the Ishikawa diagram, which is also called a fishbone or cause-and-effect diagram (Ishikawa, 1976). The purpose of the diagram is to describe in an easy-to-understand visual form the reasons that led to a certain consequence and to categorise them systematically. It has been described as a fishbone because of the method analyses the causes of the event, moving from the general (big fishbones) to the specific (small fishbones). Figure 1 shows a typical example of the Ishikawa diagram used in this study.

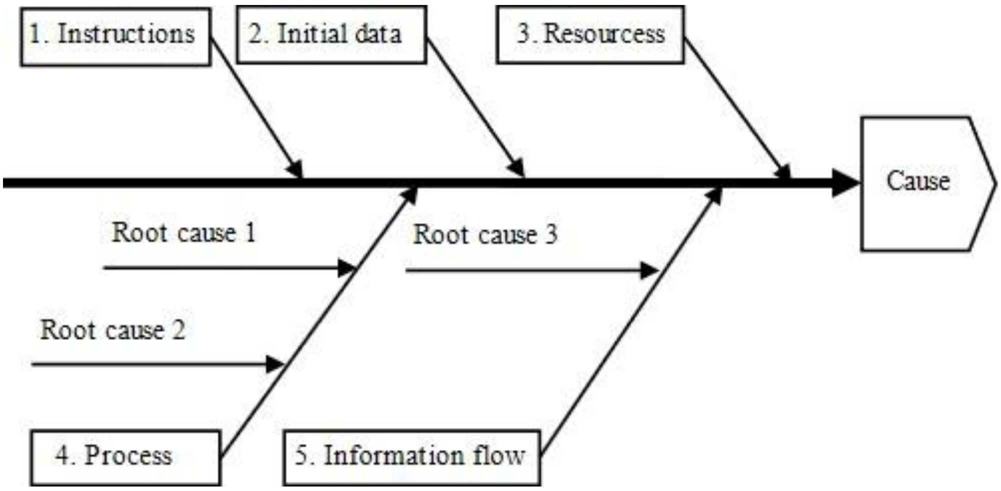

Figure 1: Ishikawa diagram in this study

Ishikawa emphasised the method's potential for learning: simply participating in the creation of the diagram is educational (Martínez-Lorente et al., 1998). However, the RCA assumes that causes or events related to an event are related to each other, and by following these interrelationships, it is possible to determine where the problem originated. RCA has become popular in daily safety work because of its simplified visual representation. Moreover, if the analysis is accurate, it also saves the practitioner's time (Hollnagel, 2017, p. 188). However, problems might arise if the results of a complex world are unclear, meaningless or too difficult to understand. To address such situations, Hollnagel (2017, pp. 30–31) presented a functional resonance analysis method (FRAM) that represents a complex nonlinear approach.

FRAM is based on resilience engineering techniques, which offer an alternative way to evaluate and design complex systems (Rosa et al., 2015). The FRAM and RCA methods can be viewed as a continuum of the domino model, in which events unfold as cause-and-effect chain reactions in which the first domino to fall is the RC (Riccardo et al., 2018). Both methods can be used for the qualitative analysis of outliers, although FRAM itself can also be used to conduct a quantitative analysis (Zinetullina et al., 2021). Hollnagel (2017, p. 40) developed FRAM as a method for analysing past events, like RCA, FRAM can be used to analyse past events as well as probable future events and failures. FRAM is based on four principles: 1) things go right and wrong for the same reasons; 2) sociotechnical systems always adapt to circumstances; 3) observations of results are described as emergent; and 4) relationships and dependencies in the system's functions are described in relation to the development of the situation using functional resonance (Hollnagel, 2017, p. 41). FRAM does not focus on the probability that a single function or task will go wrong; instead, it describes what can happen during typical daily work and how variability affects the situation, either positively or negatively (Rosa et al., 2015). In FRAM, the term *resonance* is an analogy of how variability in everyday events and performance can lead to unexpected results (Adriaensen, 2019). In individual events, such as the quality of the initial information in design work or the communication between designers, there are always natural variability, which can be thought of as vibrations or oscillations, which in a certain situation can increase unexpectedly (i.e., into resonances), thus causing an unexpected event.

The current version of the FRAM process has four stages: the first step identifies the functions that make up the FRAM model; the second step characterises variability in the functions; the third step examines the connections between the functions and determines how variability can lead to an unexpected event; and the fourth step suggests ways to manage and limit the observed variability (Yang et al., 2017). Figure 2 shows a typical FRAM model in which the function is represented as a hexagon from which the functions of the event under study are connected by branches. The process of making a cup of tea is used as an example. The functions are as follows: 1) boiling water; 2) heating the teapot; 3) adding boiled water to the teapot; 4) adding tea leaves to the teapot; 5) placing the lid of the teapot on the pot; 6) steeping and waiting; 7) straining the solid parts of the tea; and 8) pouring the tea into teacups.

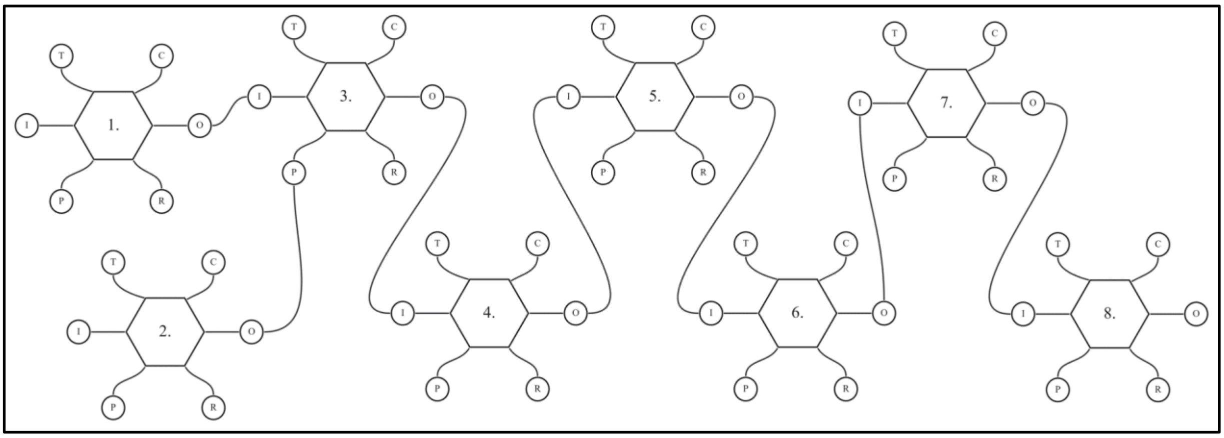

Figure 2: Typical FRAM model of the tea-making process

Variability occurs differently in functions. For example, it can arise from the machine or device used, from human activities or from organisations and social settings (Hollnagel, 2017, p. 100–106). Variability also occurs in the connections between functions, such as input, precondition, resource, control and time (Grabbe et al., 2022). For example, the output can be too fast or too slow, it can be too long or short (e.g., a machined product), it can be the wrong output (e.g., wrong information delivered), it can be too much or too little, it can leave too early or too late, and so on. As shown in the teapot example in Figure 2, the graphic description of even a simple model requires a set of interconnected function hexagons with links, which is difficult to view and interpret. Consequently, FRAM data are typically represented in table form, as in the present study (Saurin, 2016).

RCA is a well-known method used in the construction industry (Hsu et al., 2020), especially in lean construction (Enshassi et al., 2019). In lean construction, RCA is an essential and well-established component of the Last Planner® system (LPS) (Ballard, 2000; Khan & Tzortzopoulos, 2015; Abbasi et al., 2020). However, there is limited knowledge about the benefits of FRAM in the construction industry (Patriarca et al., 2020). Rosa et al. (2015) applied FRAM to identify work-related hazards on a construction site and piloted the method in the construction industry in Brasilia. Saurin (2016) also focused on the safety aspect and used FRAM in occupational safety inspections of data collected from 13 Brazilian construction sites. Ransolin et al. (2020) investigated the interactions between patient safety and well-being in a built environment using FRAM. Del Carmen Pardo-Ferreira et al. (2020) focused on concrete frameworks and modelled successes during a workday using FRAM.

This study contributes to knowledge about the use of FRAM. Neither the RCA nor the FRAM has been investigated comprehensively from a design point of view. Instead, the emphasis of previous studies on both methods has been on occupational safety. However, design work is a complex sociotechnical system that greatly affects many aspects of construction projects, including occupational safety. Therefore, focusing on the use of both the RCA and the FRAM to analyse design work is justified. The aim of this study is to use both methods to determine what can be learned about the effects of small errors and events and how the findings of the RCA and FRAM differ. The selected research approach was exploratory and data-oriented.

METHODS

SOURCE OF THE RESEARCH DATA

Because the goal of the study was to explore and learn from the RCA and FRAM methods, the research was limited to one project and three event chains. Research data were collected from a Finnish hotel renovation site of approximately 40,000 m^2, which, according to the project manager, "proceeded normally on schedule without significant problems." This was one of the basic criteria for the selection of the research site. The researchers were interested in day-to-day design work in a normally running project in which case the events under investigation would not be affected by actions and thoughts caused by major problems. A project management consultant, five design offices and the company responsible for building information model (BIM) coordination participated in the study.

APPLICATION OF ROOT CAUSE ANALYSIS

The RCAs were conducted to explore the cases to gain as many insights as possible. The aim was to gather information on the RCs of delayed design activities and the chain of events that led to delays. Of the 723 tasks in LPS sessions, three were selected for the study and subjected to detailed RCAs. The selection of topics was based on the following four principles: 1) the topic involved one or more delayed design tasks (suitability); 2) the events of the topic were ongoing during the research (timeliness); 3) the project management evaluated the study of the topics to determine their usefulness for the project (practical relevance); and 4) the topics were suitable for research (academic interest). The RCA consisted of four steps: 1) preparation; 2) open group interviews; 3) analysis; and 4) cross-comparison.

RCAs were prepared by consulting plans, meeting minutes and relevant emails. This information was provided by the project management and collected from the project's cloud service. The researcher also received documents and emails forwarded from different stakeholders involved in the project. The collected data were stored in the Microsoft Teams environment and then evaluated in collaboration with the project's management. This procedure was intended to provide a documented understanding of the events leading to the

RCA, in which the researcher relied on oral information from the respondents. The documentary-based researcher's understanding of the events was visualised as a swim lane diagram (Waterhouse, 2021) and sent as pre-material to the respondents. In the interviews, the case was examined using the *5 times why* method, in which the researcher observed and notated the conversations. Several rounds of interviews were conducted to allow for in-depth exploration and clarification of the issues raised.

In the next phase, conclusions were drawn from the analysis of the collected data. The classification of the RCs identified was based on Ballard et al.'s (2007) LPS method, which is commonly used by LPS users. The researchers added a fifth category related to information flow gaps. Finally, the results of the RCAs were cross-compared to find commonalities.

APPLICATION OF FUNCTIONAL RESONANCE ANALYSIS

In the FRAM analysis, the researchers identified the functions of the RCAs and added these to the spreadsheet, including a detailed description of the function and its aspects. The factors that caused variability are presented in Table 2. In this stage, the research was limited to examining only variability in outputs. Based on the table, three visual models with links connecting the functions were prepared. In the final stage, the researchers summarised potential approaches to reduce variability in the studied cases and compared the results of the RCA and FRAM. Figure 3 presents the research design.

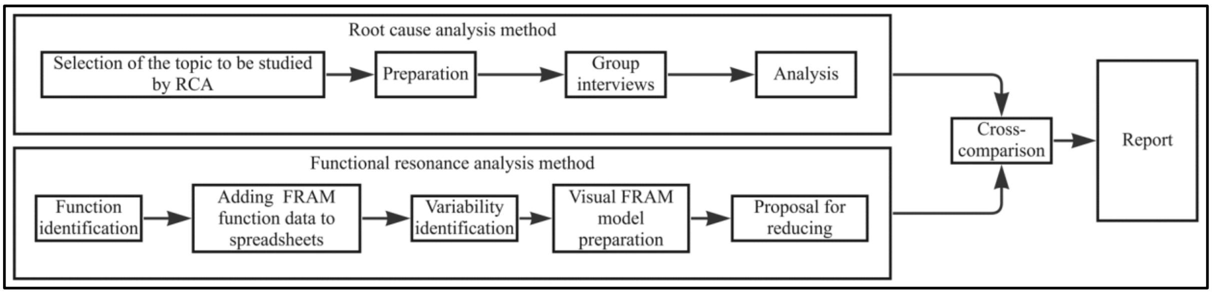

Figure 3: Research design

FINDINGS

FINDINGS OF ROOT CAUSE ANALYSES

The findings of the RCA were classified as chains of events that are represented in an Ishikawa diagram. The researchers reflected on the findings with the project management team, and based on the discussions, the RCs were assessed as appropriate and logical. The Ishikawa diagram of RCA No. 2 is presented in Figure 4.

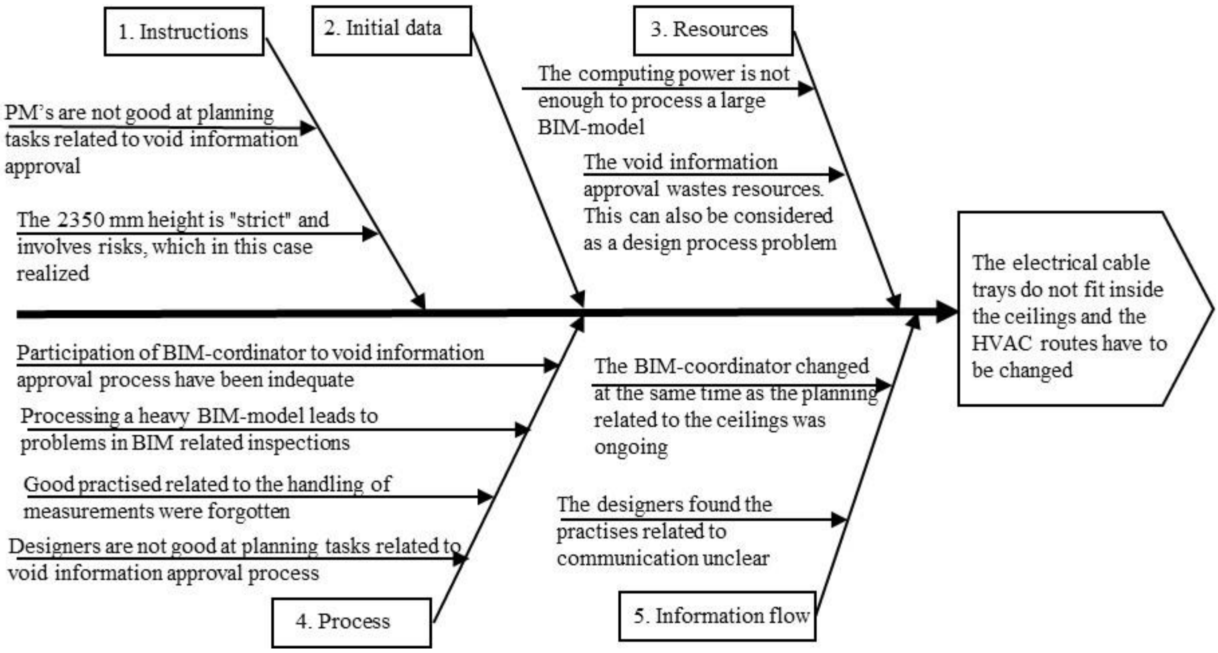

Figure 4: Root cause analysis number 2

Figure 4 presents the RCs that negatively affected the design process. A cross-comparison of RCAs is presented in Table 1.

Table 1: Summary of the Results of the Root Cause Analysis

RCA	Instructions	Initial data	Resources	Process	Information flow
1			X		X
2	X		X	X	X
3	X		X	X	X

Based on the results of the RCAs, all three cases had problems in design coordination, especially in the flow of information between designers. In all three cases, site personnel detected problems that caused stoppages in production. In all cases, there were personnel changes in the project's organisation, which were perceived in the RCA sessions as having a negative effect on the events. This was connected to problems related to the flow of information. In addition, the analyses revealed that the design was not implemented according to the pre-described process, but according to personal experience. Deviation from the process and person-centredness combined with personnel changes affected these three cases.

No observations were made regarding the initial data on the RC. However, in the RCA sessions, the respondents often referred to a lack of initial data. In all RCAs, information about the events was fragmented because it had to be gathered from several sources, and extensive networks of events were formed. The complexity of the relationships between the data and events made it difficult to identify and communicate problems.

Findings from Functional Resonance Analysis

The results of the FRAM analysis are summarised in Table 2, including the functions. Table 3 presents the output variability. Detailed descriptions of the functions have been omitted because of limitations on the length of this short paper.

Table 2: Functions and Output Variabilities

Function	I	O	P	R	C	T	Output variability (qualitative)
Case 1							
1.1 Updating LPS board	X	X	X	X	X	X	Inaccuracy: HVAC designers' task of the ventilation machine serviceability report missing from the LPS board.
1.2. Preparing a serviceability report on the ventilation machine	X	X	X	X	X	X	Late: task started late due to a task missing (serviceability report) from the LPS board.
1.3. Marking the hauling opening in the structural roof plan		X		X	X		Inaccuracy: the plan is updated needlessly, the opening is not necessary, but the data from serviceability report were late.
1.4. Marking the hauling opening in the architectural roof plan		X		X	X		Inaccuracy: the plan is updated needlessly, the opening is not necessary, but the data from serviceability report were late.
1.5. Updating the hauling opening to the structural plan	X	X		X	X		Inaccuracy: the plan is updated needlessly, the opening is not necessary, but the data from serviceability report were late.
1.6. Definition of the construction method (of the roof)	X	X		X	X		Inaccuracy: unclear communication about the construction method; task missing from the LPS board.
1.7. Commenting on the hauling opening	X	X	X	X			Inaccuracy: task for commenting missing from the LPS board
1.8. Removing the hauling opening from architectural plans	X	X		X	X	X	Late: the task was started late because the serviceability report was delayed.
1.9. Removing the hauling opening from structural plans	X	X	X	X	X	X	Late: the task was started late because the serviceability report was delayed.
1.10. Demolition work on the roof	X	X	X	X	X	X	Late: waiting for detailed drawings
Case 2							
2.1 Updating LPS board	X	X	X	X	X	X	Inaccuracy: the void information approval tasks are missing from the LPS board.
2.2 BIM coordination meeting	X	X	X	X	X	X	Inaccuracy: discussion about the unnecessary voids is missing from the BIM coordination meeting agenda.
2.3 Schedule planning for void information approval	X	X	X	X	X	X	Late: schedule planning for the void approval started after the void approval started (approx. eight months earlier).
2.4 Void information from structural designer to HVAC and EIA designer	X	X	X	X		X	Too early: the void information approval started eight months before the real need of the site.
2.5 Void information from HVAC and EIA designer to structural designer	X	X	X	X		X	Inaccuracy: lack of process or instructions for removing unnecessary voids from the BIM models
2.6 Re-routing of duct routs in HVAC BIM model	X	X		X		X	Late: due to the detected rebar on site, the HVAC ducts will have to be re-routed.
2.7 Re-routing of cable trays in EIA BIM model	X	X		X		X	Late: due to the re-routing of the HVAC ducts, the route of the cable trays must be changed.
2.8 Publishing coordination BIM model	X	X	X	X		X	Inaccuracy: Unnecessary voids are not removed from the coordination BIM model.
2.9 Observation of rebars in diamond drilled hole	X	X	X	X	X	X	Late: information about the effects of the rebars in the drilled holes is provided to HVAC and EIA designers when the technical routing was already done in BIM models.
2.10 Publication of the void drawing of the 5th floor roof	X	X	X	X	X	X	Late: HVAC re-routing delayed the release of the floor plan
2.11 Examining the need to change the ceiling height	X	X	X	X		X	Late: HVAC re-routing led to a redesign of the architects ceiling plans

Note. I = Input, O = Output, P = Precondition, R = Resource, C = Control, T = Time, EIA = Electrical, Instrumentation and Automation, HVAC = Heating, Ventilation and Air Conditioning

In Case 1, the recurring sources of variability in function output were the absence of the task from the LPS board, unnecessary design changes and starting the task late. In Case 2, recurring sources of variability were inaccurate because of unnecessary voids, which was related to a lack of process and guidelines for removing them. This issue was not discussed in the BIM coordination meetings because it was not on the agenda. Moreover, during the inspection and publishing of the coordinated BIM model, unnecessary voids were not addressed. A common source of variability in Case 1 was the absence of tasks; in Case 2, void approval process tasks were missing from the LPS board.

Figure 4 shows the functions in Case 1 and the links between them. Although the graphical presentation is difficult to interpret because of the high number of links inherent in complex systems, it is nevertheless possible to observe the central role of the LPS board in this chain of events. The numbering of the functions in the figure corresponds to the numbering in Table 2.

In contrast to Table 2, functions marked "0" have been added to Figure 4; this control function defined cycles of the LPS sessions and board updates, which in this case was the project plan.

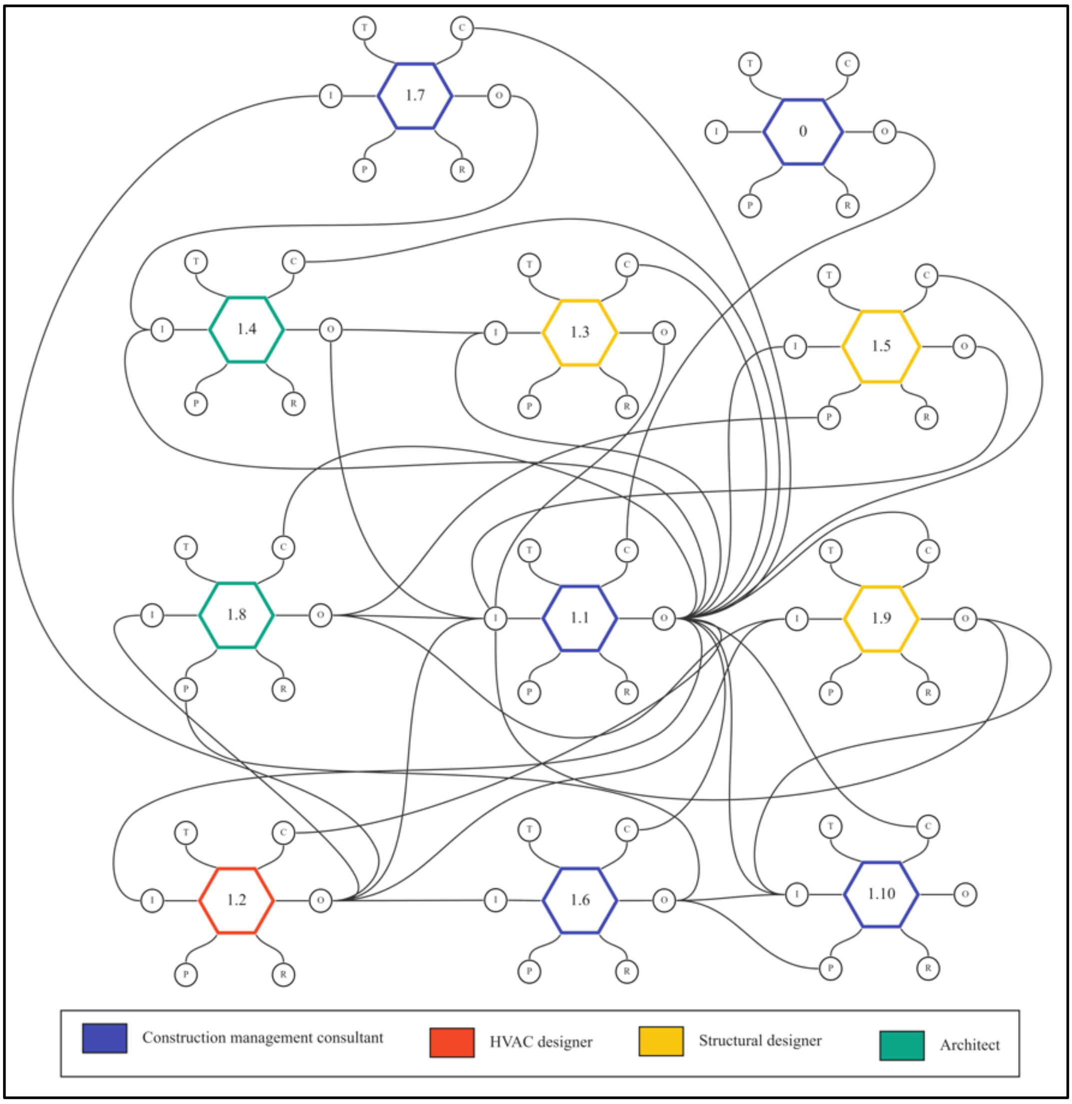

Figure 4: FRAM analysis of Case 1

As shown in Figure 4, colours were added to the functions representing the resources: blue indicates a construction management consultant; red indicates an HVAC designer; yellow indicates a structural designer; and green represents an architect. Table 2 and Figure 4 show the central role of the LPS and the variability associated with the missing tasks.

Summary of Findings

In Case 1, the RCA identified the fragmentation of information into several conflicting documents and a lack of clarity regarding the need to build hauling openings were the RCs of delay. The FRAM identified recurring variability in missing LPS tasks and unnecessary design work, which caused delays. Variability of LPS tasks prevented HVAC reporting functions from being implemented, while other functions in the system (e.g., design tasks and modelling work) continued to progress, causing unnecessary rework later in the project.

In Case 2, the RCA identified the RCs of the delay as follows: the design deficiencies of void approval-related tasks by both the construction management and the designers; the BIM coordinator's low participation in the void approval process; unclear communication by the construction managers; lack of computing power in the computers used for BIM coordination; insufficient tolerances for the renovation site; deficiencies in the presentation of dimensions in the drawings; and key personnel changes in BIM coordination. In Case 2, the variability identified by FRAM included the following: inaccuracy in the void approval process; and variability in the outputs of the three functions, which can also be defined as incomplete coordination. Time variability occurred in both directions in Case 2: void approval began eight months before the real need of the site, which was too early. Correspondingly, these tasks were planned eight months after the work began, which was too late.

DISCUSSION

The investigation of the RCs confirmed that chains of events in the design process are complex and involve multiple design disciplines (Bertelsen, 2003; Luo et al., 2017). Researching such complex, albeit daily, design-related tasks and chains of events by applying RCA was time-consuming. This may be one reason that learning-from-mistake techniques, such as RCA, are not widely used in construction and design (Dave et al., 2015). However, several interesting results were revealed by the RCAs.

In the RCAs, the initial data usually emerged as the respondents' answers to the first "why" question, but as the analysis progressed, the importance of the initial data decreased. In none of the three cases was the lack of initial data identified as the RC but a consequence of an actual RC. Although the sample comprised only three RCAs, this result was interesting, especially in terms of the typical narrative often heard by project designers, that is, a "lack of initial data". This finding contradicted those of previous studies in which a lack of initial data was often identified as the most important RC in design deviations (e.g., Khan & Tzortzopoulos, 2015; Koskela, 2004). This contradiction raises a question that should be investigated further: Does using RCA lead to a deeper and novel understanding of the RCs of design problems? For example, the event, "the drawings printed from the BIM model are incorrect", which was the cause of the delay found in the RCA, can be first classified as "initial data". However, the event "the BIM model has void reservations that are not needed" can be classified as a "process" because the void approval process was inadequate in this case. The RC was suggested to be the initial data, but after further investigation, the real situation was comprehended by the participants, and the actual RC was changed. This finding is consistent with that of Parchami et al. (2019).

The RCAs also supported previous research on the significance of planning person-centredness and key personnel changes for the success or failure of planning, as in the three cases in the present study. In a construction project, key personnel are subject to turnover, which can have serious effects on its progress (Chapman, 1999). Combined with the turnover of design experts and variability in their expertise (Manavazhi, 2004; Wang & Leite, 2014), the phenomenon observed in the results of the RCA is a model example of the variability related to the resource link used in the FRAM method.

In this study, the basic form of the FRAM was used because the researchers aimed to explore its applicability to design work. The basic form of FRAM has six characteristics: input, output, precondition, resource, control and time. However, as Hollnagel (2017, p. 194) pointed out, nothing prevents the use of other characterisations in applying this method. This freedom creates interesting possibilities, such as in design and lean construction. For example, in design, one characteristic could be value (Salvatierra-Garrido & Pasquire, 2011), and in the context of lean, one characteristic could be flow (Tommelein et al., 2022). Managing variability in these two properties is important for the operation of the system (Mossman, 2018; Lehtovaara et al., 2021). However, when new characteristics are added to the method, it should be considered that FRAM aims to determine how everyday activities are conducted. Therefore, adding, changing or removing characters should not weaken the underlying principle of the method.

Although the application of RCA and FRAM to the same chain of events yielded differing results, combining these methods could improve learning from mistakes in the construction industry. For example, the reason for the low use of RCAs (Dave et al., 2015) could be that a conventional construction project involves several tasks. On average, two-thirds of LPS tasks are completed on time (Aslam et al., 2020). Hence, when LPS is used, an RCA should be performed on one-third of the activities each week. In the example used in the present study, the LPS board contained 723 tasks, of which, according to the above principle, 241 RCAs would be performed. One author of this paper used four RCAs in his entire master's thesis. Therefore, it would have taken the working hours of 60 master's degree students to study two-thirds of the delayed LPS tasks in this hotel project, which is too much work to achieve an accurate and precise RCA. Could the FRAM perspective, which focuses on reducing variability in functions and the links between them, be a less resource-intensive way to learn from mistakes? Alternatively, could a FRAM analysis of RCA practices in the LPS session help better understand why RCA is so time-consuming? These questions and the use of FRAM in practice should be investigated further in construction studies.

CONCLUSION

This study applied the FRAM and RCA methods to two chains of events in design work. The findings showed that variability in event chains may have potential importance for the construction industry. The findings on the use of RCA and FRAM differed, which raised the question of whether the joint application of these methods could lead to learning from mistakes in the construction industry. The systemic perspective of the concept of variability in FRAM revealed aspects of the process that differed from traditional RCA. This focus on the variability of FRAM may be useful for lean construction researchers and practitioners, although further research and experiments are needed. A significant limitation of this study was the limited amount of data on only two chains of events in one geographically limited renovation project. Future research is recommended to explore a larger amount of diverse data (both by project type and geography), which could yield a more holistic picture of the RCs of design delays and provide further insights into their analysis. Further limitations are that the FRAM was focused on learning in daily work, which was hindered by the retrospective approach used in this study. Regarding learning from variability in daily work, FRAM may facilitate researchers and practitioners because the method does not require the existence of faults, errors or delays, which may enable the discussion of systemic problems without feelings of guilt, which often hinder the use of RCA.

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A FRAMEWORK FOR DESIGN WASTE MITIGATION IN OFF-SITE CONSTRUCTION

Danial Gholinezhad Dazmiri[1] and Farook Hamzeh[2]

ABSTRACT

The recent global pandemic has presented unprecedented challenges to the construction industry's survival. Therefore, even minor improvements and the elimination of small sources of waste are crucial. Although they constitute a small percentage of total construction costs, hasty designs and design errors have the potential to be one of the most significant sources of waste within the industry. Also, offsite construction involves a high degree of precision and efficiency. Any waste during the design process can result in time delays, cost overruns, and suboptimal final product performance. The design process should aim for minimal waste to avoid potential delays or errors during construction or manufacturing that could lead to wasted resources and money. To address this challenge, a framework based on lean principles has been developed to minimize waste during the design process for offsite construction.

The primary objective is to incorporate lean principles and tools to address waste reduction quantitatively and measurably. Proposed solutions aim to eliminate or reduce these activities, and a framework is presented to guide organizations in mapping out the necessary steps. To assess the recommended interventions, statistical analysis and simulation methods are introduced. The framework is intended to help evaluate processes and increase efficiency during the design phase for off-site construction and built-to-order companies. The innovation of this framework lies in its precise procedures and guidance for improving these phases using Lean tools, which could provide significant benefits for off-site construction and built-to-order companies.

KEYWORDS

Off-site construction, waste, value stream, design science, simulation.

INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry is known for its dynamic nature and variability, making it challenging to achieve efficiency. As defined by researchers, efficiency is utilizing the fewest resources necessary to perform a job (Wandahl et al., 2021). In the context of Lean production and construction, the fundamental objective of efficiency enhancement is reducing waste and adding value (Koskela, 2000). The AEC industry generates substantial waste (Bølviken and Koskela, 2016). It has been utilizing Lean technologies such as Just in Time and Last Planner for the past two decades to reduce this waste.

In the context of Lean, waste refers to the improper use of time, money, or other resources due to inefficient utilization of machinery, supplies, employees, or other assets (Formoso et al.,1999). It is defined as any work or resource that does not add value to the product (Koskela,

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1992). According to Womack and Jones (1996), "any activity" that consumes resources without adding value is considered waste in design. Time is a valuable waste indicator, particularly when assessing the proportion of non-value-adding tasks. Delays, waiting, design flaws, excessive processing, and negative iteration or rework also contribute to waste in Design (Ballard, 2000; Tzortzopoulos et al., 2020). Such wastes can significantly impact building projects, with design errors primarily contributing to cost and value loss (Tzortzopoulos et al., 2020). Rework and non-value-adding activities during the design process can also prolong the time required for design improvement and cause delays (Mryyian & Tzortzopoulos, 2013).

While many construction components are mass-produced (made-to-stock), some essential components are designed, manufactured, and delivered on demand (Build-to-order) in fabrication shops (Ballard & Arbulu, 2004) as part of the off-site construction industry. While off-site construction has many benefits, such as shorter construction times, less waste, better quality, cost-effectiveness, flexibility, and increased safety, it also has some limitations and challenges (Hussein et al., 2021), such as delayed design information receipt, frequent design revisions, altered installation timing and sequence, and demand variability (Ballard & Arbulu, 2004) and improper design work (Pasquire & Connolly, 2003).

Despite accounting for a small percentage of total construction expenses, proper design is essential for the long-term success of a project, as it affects everything from customer satisfaction to operating and maintenance expenses (Kalsaas et al., 2020). Hasty designs, design processes, and design management practices are at the root of many long-standing production and construction issues (Pikas et al., 2020). During the construction and maintenance of buildings, design errors have been the leading cause of structural failures, time and cost overruns, and catastrophic accidents (Chapman,1998; Love & Li, 2000; Love et al., 2008; Pikas et al., 2020). Rework, change orders, and preliminary estimates, resulting from poor designs, lead to overbudget spending or delays and are potentially one of the AEC industry's most significant sources of waste (Breit et al. 2008).

Several studies aim to enhance the design process in the AEC industry, focusing on integrating design with modern technology such as BIM to increase efficiency. However, there are few studies on mitigating waste in the design process, particularly in midsize and small size built-to-order plants for off-site construction. This research uses lean principles to evaluate and analyze waste in the design process, identify non-value-adding activities or processes and propose solutions to eliminate or reduce them in offsite construction. This research offers a framework for standardizing the identification and elimination of waste to assist organizations in improving their productivity and reducing costs and time. This framework addresses the challenges encountered in off-site construction and built-to-order production, including low utilization of processes, prolonged design lead times, and negative iterations. By evaluating and analyzing waste in the design process through lean principles, this framework aims to identify non-value-adding activities or processes and provide solutions to eliminate or reduce them. The proposed framework provides a transparent and standardized approach for organizations to follow in order to improve efficiency and optimize the design process in off-site construction and built-to-order production.

METHODOLOGY

The methodology adopted in this study is Design Science Research (DSR). DSR is a methodology that aims to enhance human understanding by creating new artifacts (Brocke et al., 2020). This methodology includes three steps: problem identification and objectives definition, designing artifacts to address the problem and evaluating the artifacts using a case study.

The initial step involves identifying the problem and justifying its significance, as posited by Brocke et al. (2020). To ascertain the issues that may arise during the design phase, a comprehensive review of the relevant literature was conducted, as mentioned in the last section, to identify potential problems and sources of waste.

For the second step, a case study was selected as a primary data-gathering source to better understand the design phase within off-site construction. Following an exhaustive analysis of the case study, coupled with the execution of interviews, the research objective was established to incorporate lean principles and tools to quantitatively and measurably address waste reduction. This study focused on a case study of Company X, a build-to-order offsite construction/manufacturing company in Alberta, and its design processes and procedures. To collect data, two methods were used: Semi-Structured Interviews and an Enterprise Resource Planning (ERP) database. The first method used for problem identification was structured interviews. The proposal for the study was submitted to the Research Ethics Office of the University of Alberta with all necessary information and sample interview questions and was approved by the mentioned office. Multiple interviews were conducted to understand the design process better and identify any missing information.

Along with a focus group interview with the design team, 17 interviews were conducted with the general manager, design manager, designers, production manager, order desk manager, and operations personnel. Focus group interviews are in which participants are encouraged to interact and share their thoughts and insights. A focus group interview with the design team can provide valuable feedback on the design process. It was found that the ERP system poses significant challenges and causes excessive processing time within the process. Additionally, the number of revisions due to customer feedback is high. During the interviews, the interviewees were also asked to estimate how long it would take them to complete their design tasks and the probability of rework in the design process. These probabilities can be used to estimate the system's rework, revisions, and Yield.

Data was also collected from the ERP database. There are two types of jobs based on the lead time in this process: Standard and Rush delivery. Standard delivery jobs are prioritized according to the order in which they were received, while rush deliveries are given priority in all cases, and designers begin working on them immediately. Due to their exceptional nature, rush deliveries are not included in the analysis. Based on the classification of jobs, there are four distinct categories. In retail, a customer is an individual person, and the company directly interacts. Builder, where the customers are developers and construction companies. Dealer, where the customer is typically another architecture firm or office that has utilized the manufacturing services of Company X. Lastly, Project, where the customers are primarily construction companies, and the job pertains to high-rise buildings with repetitive designs.
The duration of each step in the design process was calculated as a probabilistic distribution to reflect the actual situation more accurately.

For the third step, a robust framework was developed after consulting with the experts involved in the case study and thoroughly scrutinizing the measures necessary to identify and reduce waste. The framework specifically targets the design process, improving it through digitization and providing quantitative evidence using a simulation model. The framework employs value-stream mapping, a powerful tool for identifying and analyzing a process's current state and forecasting future processes after minimizing waste. The mapping exercise aims to identify waste areas in the design process, such as rework, multiple revisions and waiting time or latency, and provide a general guideline that outlines clear and concise step-by-step approaches for suggesting and implementing improvements to mitigate process waste.

The first stage of the framework is the definition stage, where the method of data collection and the type of information that needs to be collected as input for the process are defined. It is crucial to identify the metrics to understand how to evaluate the desired outputs and what types of outputs are expected to be controlled to identify waste. Figure 1 shows the proposed framework. The identification stage is the next step, where data is transformed, and the current situation is analyzed to find waste using value stream mapping. The way to map the value stream was adopted from Rother and Shook (1999). At the end of this stage, a simulation model was developed to get visibility into the process. The proposed framework is presented in Figure 1.

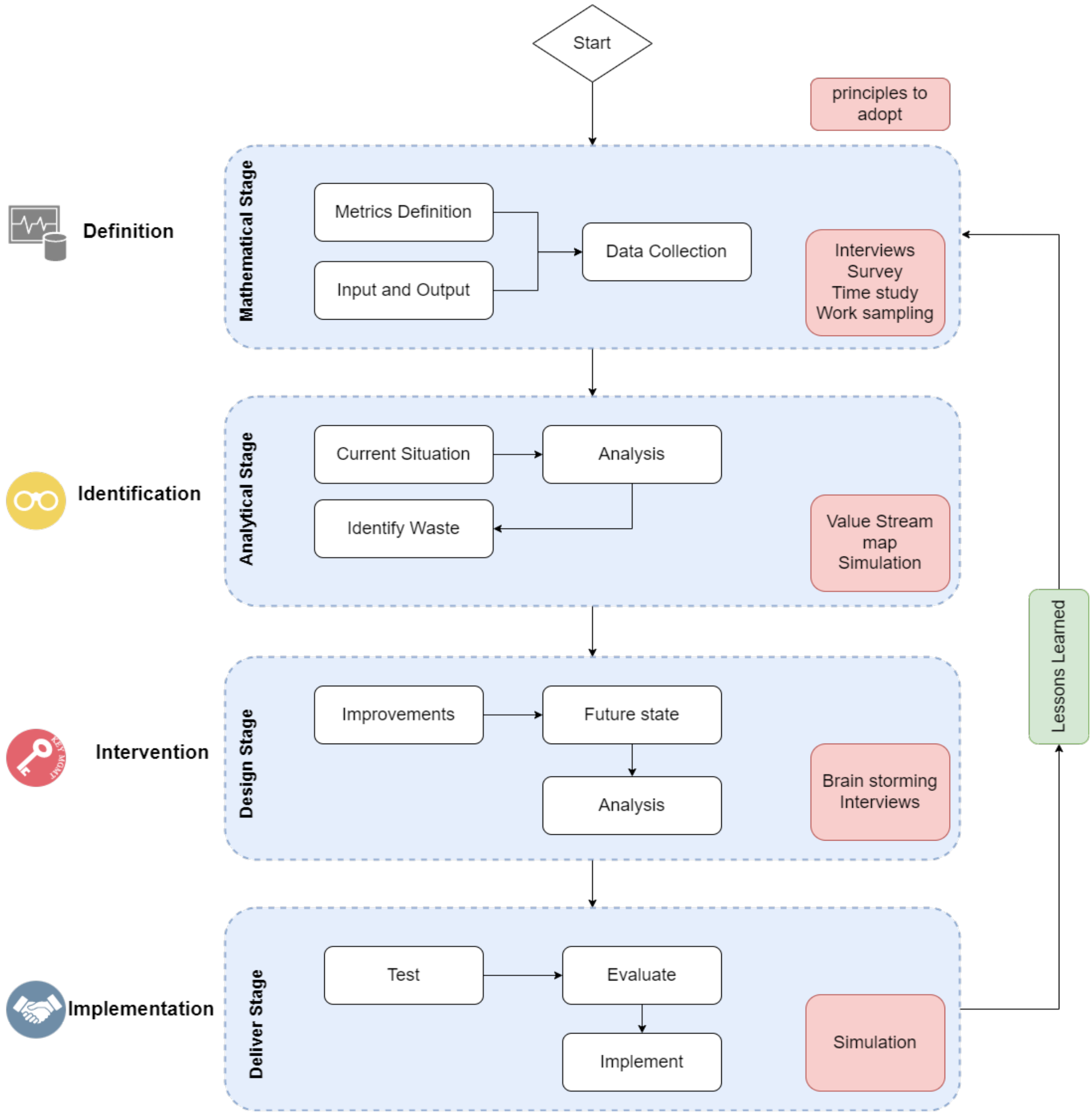

Figure 1: Proposed framework for identifying process waste.

The design stage is the third stage, where artifacts and interventions are created to address the process waste identified. At this stage, the improvements were determined by conducting expert interviews or conducting a brainstorming session with them to forecast how the process would develop in the future. The final stage of the suggested framework is to test the improvements and validate the beneficial effects on the process using the model developed in stage two. Before implementing these improvements, one must ensure their effects on the process and the organization. This can be accomplished using simulation to verify both present and potential future conditions. The company could put their improvements into practice after they are proven to be successful. This framework is generic and may also be used by others. This framework will aid and standardize efforts to boost productivity by reducing the number of non-value-adding activities.

The proposed framework reflects a comprehensive and integrated approach designed to optimize resource utilization, minimize waste, and enhance the overall efficiency of the design process in off-site construction. Statistical tools are applied to evaluate the framework, which is tested through simulation and recording of results.

Before developing the simulation model, several metrics were adopted as well to analyze the captured data. The first one was the Utilization Ratio (Equation 1), which compares the total process time (DPT) with the overall lead time (DLT). The potential for improvement in operational efficiency can be significantly increased when there is a significant difference between operational time and lead time (Berndt et al., 2016).

Another metric for assessing process performance was the Rolled Throughput Yield (RTY), which evaluates the overall performance of a process by calculating the Yield for each process phase (Graves, 2002). The Yield, or success rate, represents the percentage of units that pass through a process without defects. Rework is often an indicator of design defects. By knowing the percentage of defects per unit (dpu) for each process step, the Yield for each step could be calculated using Equation 2, and the RTY could be calculated by multiplying the Yield of each step, as shown in Equation 3.

Equation 1: Utilization Ratio = DPT/DLT

Equation 2: Yield = e ^ (-dpu)

Equation 3: RTY = $Y_1 * Y_2 \ldots * Yn$

Because the time required to complete a task varies depending on the designer and job, the data must be fitted to specific distributions to calculate task duration. These distributions can be computed using software such as EasyFit and evaluated using the Kolmogorov-Smirnov (K-S) test.

The simulation validated the design process's current state and evaluated the proposed intervention's impact. Once validated, simulation was used to evaluate the impact of each proposed intervention and its combinations. Simphony.Net 4.6.0 was used to develop the simulation model and test the improvements to the design process. The simulation model was generated based on the general template and elements of the Simphony, presented in Figure 2.

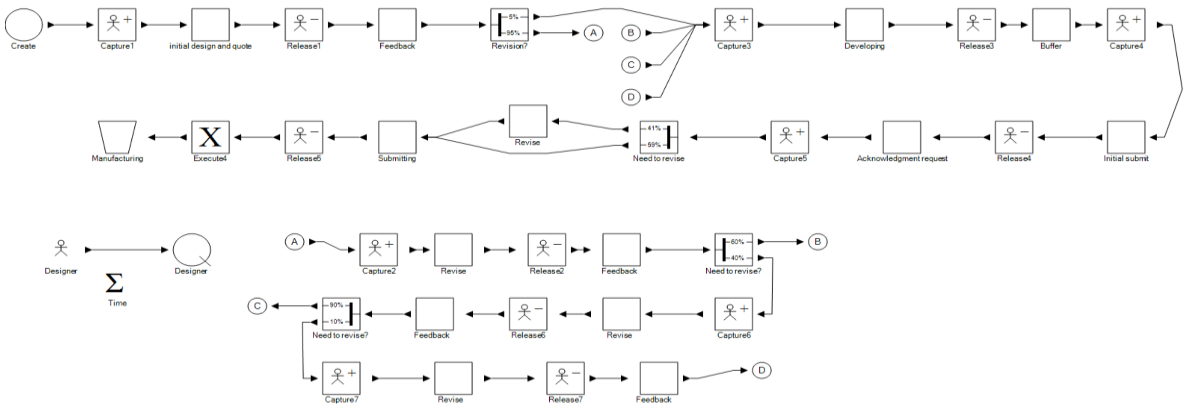

Figure 2: The general layout of the current state map simulation

Multiple approaches were used to verify that the model accurately represents the target concept to ensure the created simulation model's accuracy. These approaches were based on the methodologies proposed by Al-Hattab and Hamzeh (2018) and included verifying the consistency of input and output data, monitoring the logical performance of the model through basic indicators, and making the appropriate modifications to ensure an accurate simulation.

Through the monitoring of these approaches, it was determined that the model was correctly implemented. Additionally, the case study model, its input and output, were presented to experts for validation. It was confirmed that the simulation results accurately reflect the real-world process being studied. It is important to note that while the simulation results indicate a significant reduction in design lead time, the research method has limitations, and the results should be interpreted with caution.

RESULTS

From the data collected, it has been determined that, on average, the initial designs require 2.5 revisions. The probability of the design being revised for the first time is 95%, and for the second time, 45%. During the interviews, the interviewees were also asked about the challenges and threats in the design process that could cause waste or non-value-added activities in the system. Table 1 shows the results from the interviews regarding the task durations.

Table 1: Task duration results from interviews

Task	Unit	Time			
		Optimistic	Most probable	Pessimistic	Average
Designing the initial designs and quote package	hours	2.44	3.4	5.8	3.63
Getting feedback from the client	days	2.2	4.2	10	4.83
Revising the designs based on the feedback	hours	1.3	2.3	4.4	2.48
Revising the designs a second time	hours	0.5	1	2	1.08
Developing final package	hours	1.2	2.4	4.2	2.5
Reworking because of the initial blueprint	hours	1	1.7	2.8	1.77
Generating the contract	hours	0.45	0.7	1.05	0.71
Building the file in the ERP	hours	0.3	0.45	0.85	0.49
Receiving feedback from the control department	days	2.8	4.2	6.6	4.37
Making final changes based on an acknowledgement	hours	0.3	0.6	1	0.61
Submitting final copy	hours	0.35	0.55	1.1	0.60
The whole design process	days	16.4	47.3	106.4	52

The proportion of each delivery type can be seen in Figure 3, and general information on each class is summarized in Figure 4.

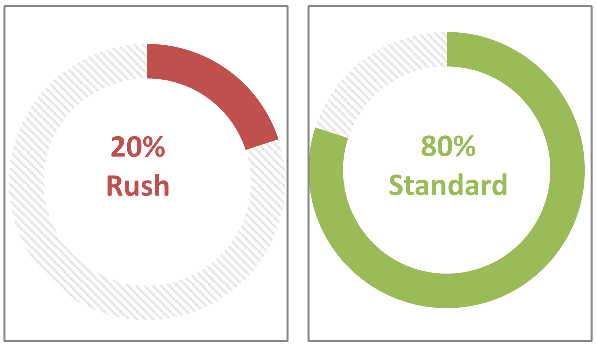

Figure 3: Type of job delivery in Company X

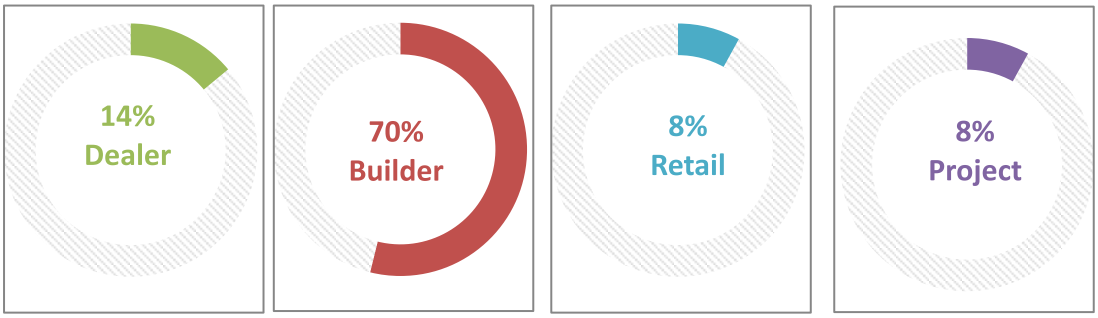

Figure 4: Available data on each job category

Upon completing the current state map, evaluating the parameters identified for value stream mapping is essential. The first parameter to evaluate was Design lead Time (DLT) and design process Time (DPT) which were 50.74 and 4.16 days, respectively. Using these two parameters, the Utilization Ratio is 8.2%. The rolled Throughput Yield (RTY), calculated using Equations 2 and 3, is 13.95%.

The case study highlights the need to improve the design system and process to increase efficiency. These improvements can be made at three levels: the designer level, the organizational level, and the client level. Addressing waste at the designer level is the most targeted approach, while organizational-level improvements require a coordinated strategy and may involve higher costs. Lastly, addressing client waste is crucial to improving the overall design process. Table 2 summarizes the suggested interventions to improve the system and process.

Table 2: Suggested improvements for the case study

#	Interventions	Related Challenge	Improvement
1	Reducing negative iteration	Insufficient information	Client
2	Reducing the waiting time	Waiting time	Client
3	Increasing Yield in the initial submission	Design errors	Designer
4	Levelling the process	Workforce	Organization
5	Reduce the redundancy associated with	Redundancy in the process	Organization
6	Using new drawing software	Drawing software restrictions	Organization
7	Reducing acknowledgment waiting time	Waiting time	Organization
8	Reduce buffer time after the contract	Buffer	Designer

The scenarios for the system's future state were developed by incorporating the interventions outlined in Table 3. Initially, individual interventions were simulated. However, as there is potential for more significant improvements, Intervention Combinations (IC) were constructed by combining two, three, four, and so on, up to eight interventions. It should be noted that due to the complexity of the existing system, it may be difficult to implement multiple interventions simultaneously. A total of 255 ICs were constructed and simulated to evaluate the system under different conditions. The simulation results indicate that implementing multiple interventions results in a more remarkable improvement in the design process. The combination of all eight interventions shows the most significant improvement, with a 47.3% reduction in design lead time and an increase in utilization ratio to 13.7%. This highlights the importance of considering a holistic approach when implementing changes in the design process. Table 3 shows the most significant reductions in DLT, and Figure 4 also shows the DLT for different interventions.

Table 3: Simulation results for intervention combinations based on DLT reduction.

Intervention Combinations	DLT (days)	Utilization	RTY
1&2&3&4&5&6&7&8	27.79	0.137	0.39
1&2&3&4&6&7&8	27.99	0.136	0.39
1&2&4&5&6&7&8	28.35	0.134	0.26
1&2&3&4&5&6&7	29.64	0.128	0.39
1&3&4&6&7&8	29.65	0.128	0.39
1&2&3&4&5&7&8	30.28	0.132	0.39
1&3&4&5&6&7&8	30.3	0.125	0.39
1&2&3&4&6&8	30.4	0.125	0.39

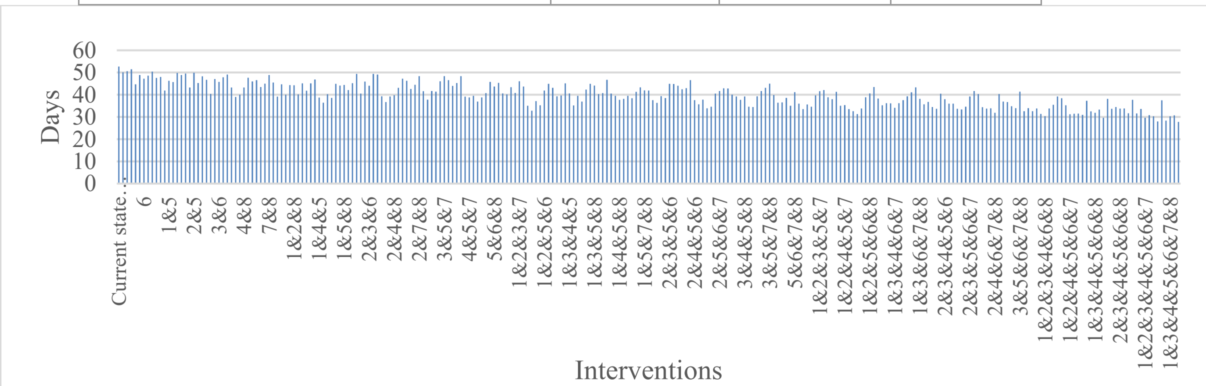

Figure 5: Design Lead Time for suggested interventions

The value classification pr project for the current state situation and implementing eight interventions is presented in Figure 5, showing a considerable improvement in reducing non-value-adding activities.

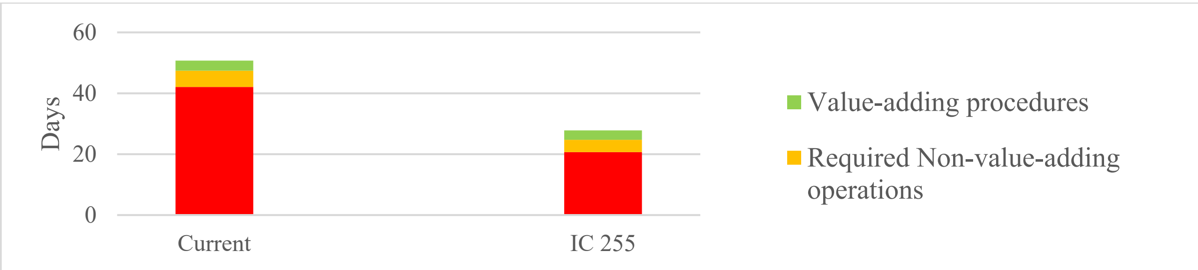

Figure 6: Value classifications per project

DISCUSSION

After eliminating irrelevant data and information, the Value Stream Mapping (VSM) was performed. As previously stated, VSM helps to gain a more comprehensive understanding of the process. The first parameter to evaluate is the average Design Lead Time (DLT), which is 50.74 and Design Process Time (DPT) is calculated to be 4.16 days, which shows that if there was no disruption in the flow of information, design jobs should go through the whole process in only 4.16 days. Compared to the time it takes to go through the process, the Utilization Ratio is found to be 8.2%, indicating that only 8.2% of the time allocated for design is used for the actual design process. While the time buffer in the process may be attributed to a designer's workload, the utilization rate of 8.2% is still deemed insufficient.

Another critical parameter to calculate is RTY, calculated by considering the number of reworks and revisions required for each job and is used to determine the Yield for each station. As per the calculation, only 14% of design jobs pass the process without defects. This low percentage indicates room for improvement in the design process to reduce reworks and revisions.

Numerous iterations between the customer and the designers often hinder the design process. This can be caused by a lack of clear direction from the client or inadequate information from the marketing team. Communication gaps and requests for minor design changes between designers and other departments also contribute to this challenge. Currently, revisions in the design process are a source of waste. It is essential to focus on creating more value in the initial design to reduce the number of revisions.

One of the significant challenges identified in the interviews is using the ERP system. The system is difficult to navigate and was not explicitly designed for this company. Additionally, the requirement to upload information to the ERP system and an internal server results in redundant work. This causes difficulties for designers and other employees in making changes and updating information.

Customization refers to the process of creating a product that is tailored to a specific customer's needs or preferences. This can include unique designs or patterns that are difficult to produce. All departments in the manufacturing process can face challenges when it comes to customization, particularly in areas such as design, sourcing unique materials, and production. Designers may not have the specific knowledge or skills to create the custom design that a customer requests. Finding unique materials or colours can be difficult, and purchasing small quantities can be costly. Specialized machinery and operators may be required in production, causing disruptions and increasing costs. Additionally, the production of custom designs may require more time and effort, resulting in longer lead times. To minimize these challenges and save time and money, it may be more efficient for the company to reduce variability and avoid customization by focusing on producing standard products.

The proposed interventions were simulated to assess their potential impact on the design process. The simulations included individual interventions and combinations of up to eight interventions. The results of the simulations show that levelling the process and implementing new drawing software and generative design approaches have the most significant potential to improve the design lead time, resulting in a 15% reduction in DLT and a 17% increase in the utilization ratio. Additionally, interventions 1 and 3 effectively reduced rework and increased Yield, as evidenced by improvements in RTY.

It is anticipated that the implementation of all interventions will result in a reduction of time for not only non-value-adding activities but also required non-value-adding and value-adding activities. This presents an opportunity to optimize the system and increase efficiency.

This study validated the proposed framework and interventions by surveying the company under examination. A 5-point Likert scale was utilized in the questionnaire to gather feedback on the effectiveness and applicability of the interventions, with scores ranging from 1 (very poor) to 5 (excellent). The results of the survey are presented in Table 4.

Table 4: Survey results for evaluating the effectiveness and applicability of interventions.

Interventions	**Effectiveness**	**Applicability**
1: Reducing negative iteration	4	3
2: Reducing the waiting time for feedback	3.5	3.5
3: Controlling the designs	4.5	4.5
4: Add additional designers as needed	4	3.5
5: Reduce the redundancy	4	4
6: Using new drawing software	4.5	3
7: Reduce waiting time for the Order desk	4.5	3.5
8: Reduce buffer time after the contract	4	3

Overall, the proposed interventions effectively reduced waste and improved the design process. However, there are some concerns regarding implementing specific interventions, such as collecting customer feedback in a timely manner and the unfamiliarity of designers with new software. These concerns can be addressed through further training and education to ensure the successful implementation of the proposed solutions. Additionally, reducing the invoice validation period may be challenging and requires further examination to identify ways to reduce the buffer time after the contract effectively.

CONCLUSIONS

This research aims to develop a methodology to improve the design process by identifying and eliminating waste and non-value-adding activities. This research primarily employs value stream mapping as the method of investigation and simulation to evaluate the proposed improvements. Various methods were employed to gather data on the duration of each task in the design process and to provide a statistical overview of the process.

The proposed framework aims to provide organizations with a systematic approach to identifying and addressing waste in the design process. The framework utilizes various Lean tools and methodologies, such as statistical analysis and simulation, to evaluate and improve the efficiency of the design phase in off-site construction and built-to-order companies. The simulation results indicate a significant design lead time and utilization ratio improvement due to implementing the proposed interventions. However, it is essential to note that further cost reduction can be achieved by implementing additional Lean tools. The proposed framework is validated through an evaluation process, which compares the stated objectives to the actual outcomes of its implementation and may employ various evaluation procedures depending on the context and topic being assessed.

The objective of identifying waste in the design process in build-to-order off-site construction/manufacturing was achieved using value stream mapping as a Lean tool. This process-oriented approach allowed for the study and evaluation of the system, focusing on identifying and eliminating waste and non-value-added activities. In addition to value stream mapping, interviews and simulations were used to gather information and gain insight into the design process. These methods provided a comprehensive understanding of the process, enabling the identification and elimination of waste, ultimately leading to an improved design process.

In the case study context, additional issues required more comprehensive managerial solutions. These issues were rooted in the high level of customer involvement in the design process, which resulted in increased variability and a need for rework. This challenged the designers and made it difficult to standardize the design process.

The limitations of this research should be acknowledged. One limitation is that the data collection method used was interviews with a limited number of experts, which may not fully represent the entire population. The study did not consider the participants' demographic characteristics, which could have provided more results. Furthermore, only a few process classes were mapped using value stream mapping, which may not have captured the full scope of the process. Additionally, the metrics used to monitor waste were limited to time and reworked, and other factors could have been beneficial for identifying hidden waste within the process. Furthermore, the proposed interventions were based on the availability of technology for small and medium-sized businesses, and future research could benefit from evaluating other interventions and their impact on the design process. Finally, future research could explore the development of a digital platform or dashboard to integrate all design processes and tools, including enterprise resource planning (ERP) and design software, which could aid professionals in reducing waste and increasing value delivery.

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PRODUCT PLATFORM FLOW TO DEVELOP NEW PRODUCTS IN AN OFF-SITE COMPANY

Tainara P. Nievola[1] and Sergio Scheer[2]

ABSTRACT

The civil construction's cost has increased since the beginning of the pandemic, bringing insecurity to the sector. In addition, civil construction is largely responsible for environmental impacts related to greenhouse gases and waste generated globally. Several industries, such as the auto industry, use the product platform concept to optimize their processes, bringing more efficiency and control to their productions and products. The existing theory on the application of a product platform in construction shows that it can be a means of controlling fluctuating costs and reducing environmental impacts, but there is a gap, with few studies showing the application in real cases and the gains obtained. To assess this, the literature review aims to understand how product platforms work in other industries and what we have so far on their application in the construction sector. An action research method is used, applying the product development flow created, to meet two demands for new products in the studied company, using other platform solutions already developed by the company – such as application of common items - to achieve cost reduction. The result of the practical application reached the company's expectations, achieving a significant cost reduction.

KEYWORDS

Product development, product platform, off-site construction, industrialized construction, standardization.

INTRODUCTION

From January 2020 to January 2022, the annual increase cost of Brazilian civil construction more than doubled in relation to the period from January 2018 to January 2020, as can be seen in Figure 1 (FGV, 2022). And even though the index shows a reduction in 2022, it is still considerably above the index in the pre-pandemic years. According to European Commission (n.d. a) data on construction cost indexes, in Europe, between 2011 and 2016, cost increases were around 1.5% per year, from 2017 to 2019 around 2.3% and even though in 2020 it kept stable, in 2021 the cost increase in construction averaged 6.5%.

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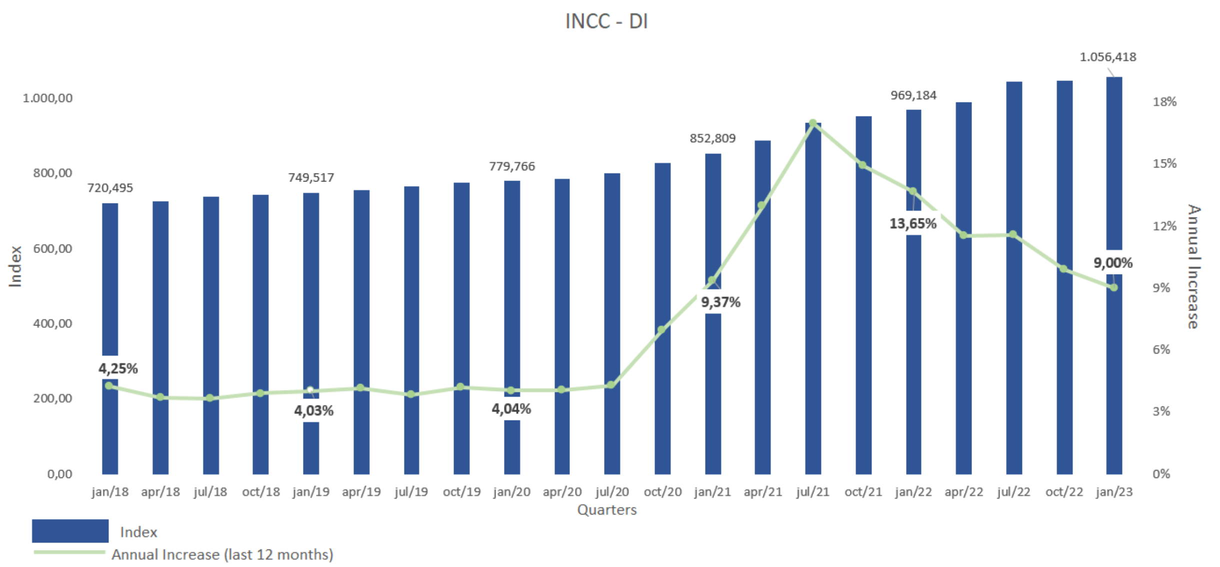

Figure 1: National Civil Construction Index (INCC) variation. Adapted from FGV, 2022

Besides, constructions and demolitions are responsible for 44% of the waste produced by industrial sectors annually (Chen et al., 2022). Along the same lines, Liu et al. (2015) report that in England, activities related to construction and demolition are also responsible for 44% of all waste generated. On a global scale, around 40% of the material dumped in landfills is construction waste (Banihashemi et al., 2018). Waste means extra cost to the construction companies and residents.

The product platform is a strategy widely used in manufacturing such as the automobile industry (Alizon et al., 2009), it consists in identifying commonalities that can be applied to more than one project, product, or process, with the aim of creating and grouping common items (components, processes, knowledge, and people). The creation of standardizations allows product derivatives to be developed and produced more efficiently (Popovic et al., 2021 and Hanafy et al., 2017), that includes standard processes as well. Furthermore, studies such as that by Tseng et al. (2008) show how modular design and '*platformization*' can lead a product to a more sustainable lifecycle.

The existent literature brings a solid theoretical approach on general product platforms, but there are few studies showing the application in real cases and the gains obtained. This research addresses this existing gap by using the Action Research Methodology, identifying through existing literature ways in which the use of product platforms can address the cost challenges, bringing with it a gain in sustainability and then creating a new product development flow based on the reviewed literature, and applying it in the company's process observed in this study, to capture the real gains in cost reduction with the use of product platform solutions.

PRODUCT PLATFORM

The clustering of different assets (e.g., components, processes, knowledge) in order to define standards that will be used in the creation of new products is the basic concept of a product platform (Robertson et al., 1998). As Lennartsson et al., (2018) described, “Through product platforms, companies achieve high levels of product variety, a reduced time to market, improved operational efficiency and responsiveness to market needs”.

Standardization also has benefits related to a company's supply chain. As shown by UK Research and Innovation & Construction Innovation Hub, 2022, the constant and repeated use of the same components brings three main benefits:

1 – allows working with stock, which allows companies to take advantage of promotions or cost reductions to control their own production costs;

2 – allows the development of different suppliers for the same element, limiting the market control of only one supplier, which normally means high cost;

3 – reduces the risk of delays resulting from a long lead time from suppliers.

These risks of delay in the conventional construction process (due to project delays or material delivery) are further compounded by delays related to low productivity, lack of labour, and operational stoppages (strikes, absences, delays) (Bryden Wood et al., 2018). These risks are minimized or eliminated with the adoption of platform strategies.

All the benefits mentioned above can be converted into financial gain, as presented by Bryden Wood et al. (2018). The net present value (NPV) – which is the cash flow assessment of an investment in a given period – in a process with a platform approach is optimized by requiring a smaller initial investment, reducing the time to payback on this investment and increasing the value end when compared to a conventional process.

A successful platform requires a balance between custom elements, unique to each project and impossible to avoid, complementary elements, which are similar but not the same (such as colour or material variation), and standard elements, common to all projects. This balance allows companies to meet the desires of their customers (UK Research and Innovation, 2022).

The use of standardization is not unknown for general manufacturers, such as the automobile industry (Alizon et al., 2009). Within this type of industry, the customization of the final products - cars and trucks, for example - by the end customer does not involve structure, such as chassis. Their customizations include colour, electric windows and air conditioning systems, for example, that does not – or have minimal - change the production line. In civil construction, the case is different, the end customers are residents, and they tend to want a personalized house, often designed exclusively for them (Gibb, 2001). This makes the standardization process more complicated to the production line, and to address this point, there is the mass customization strategy.

MASS CUSTOMIZATION

Mass customization is a technique that firstly involves in-depth knowledge of the customer to meet their specifications using standard assets that, combined with each other, bring customization of the final product without losing scale economies (Duray et. al, 2000). A good example of this is the computing industry, which has standard modules (video cards, batteries, memory cards) that when combined can form different end computers, serving customers looking for the simplest to the most complex computers capable of running heavy software (Piller et. al., 2006).

In civil construction, mass customization can work through the architectural modularization of roof types, window and door frames, and hydraulic kit solutions, one can even think of the spatial modularization of entire environments, such as kitchens and bathrooms, even transforming electrical and hydraulic elements in default. Figure 3, below, shows standardized solutions, that combined in different ways can create different products, and helps to better understand this idea.

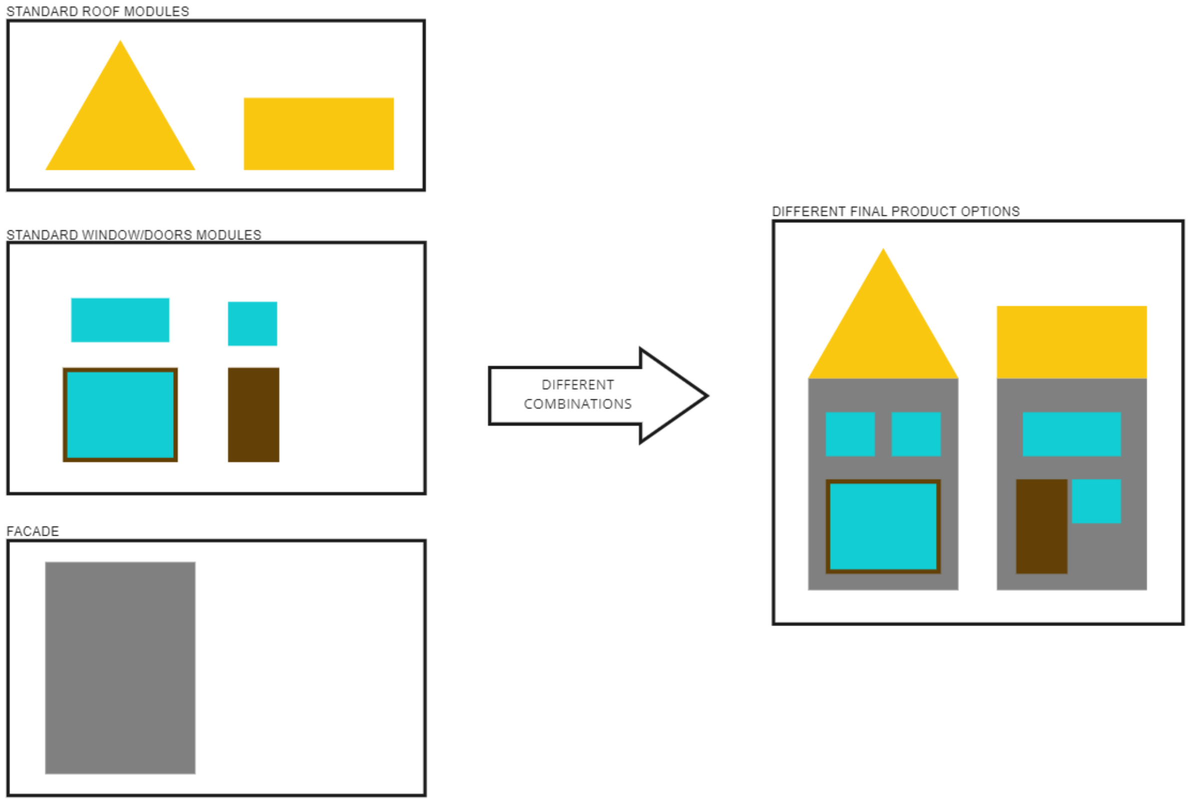

Figure 3: Mass customization in civil construction

The use of mass customization and product platforms is related to sustainability through increased efficiency since the teams that work in production only work with the repetition of modules, thus, they are able to specialize and continuously improve in what they are doing. This reduces errors, therefore reducing rework and therefore reduces the use of raw materials. Also, the participation of the customer reduces or eliminates the reforms, which reduces the waste generated with them (Rocha, et al., 2015).

In addition, as Gibb (2001) demonstrated in his case study, the repetition of modules, solutions, and processes reduces the work of the project team and brings more efficiency to the engineering team, and reduces costs and risks related to accidents at work and delays. This information is corroborated by UK Research and Innovation & Construction Innovation Hub (2022).

The greatest gain with the use of the platform exists when its application happens from the product development phase when the conception of a new product is done collaboratively with commercial, project, operational, and supply chain teams (Ortega *et al*., 2022). And integrating all stakeholders in the design stage is a challenge within civil construction (Jaillon & Poon, 2010), but it is fundamental for the success of a product (Ortega *et al*., 2022).

MAKE TO ORDER AND CONFIGURE TO ORDER

Inside a platform, the products can be placed in different categories. A new product that is fully developed (e.g., complementary projects, DfMA) before being launched in the market, fits into the Make-to-Order (MTO) category. MTO products cannot be modified by the customer, they are adamant about changes. But mass customization allows some modifications to meet customers' specifications, in this case, when a new product is developed based or not on a previously existent project, but still only uses solutions and processes that belong to the platform, they are called Configure-to-Order (CTO). Figure 4, based on Gatehouse.design (n.d.), shows the different categories, and the line is the decoupling point of the customers' specifications – the further to the right, the more specifications are created in the development phase, before the customer order, and to its left, more specifications are created following the customer order, customized.

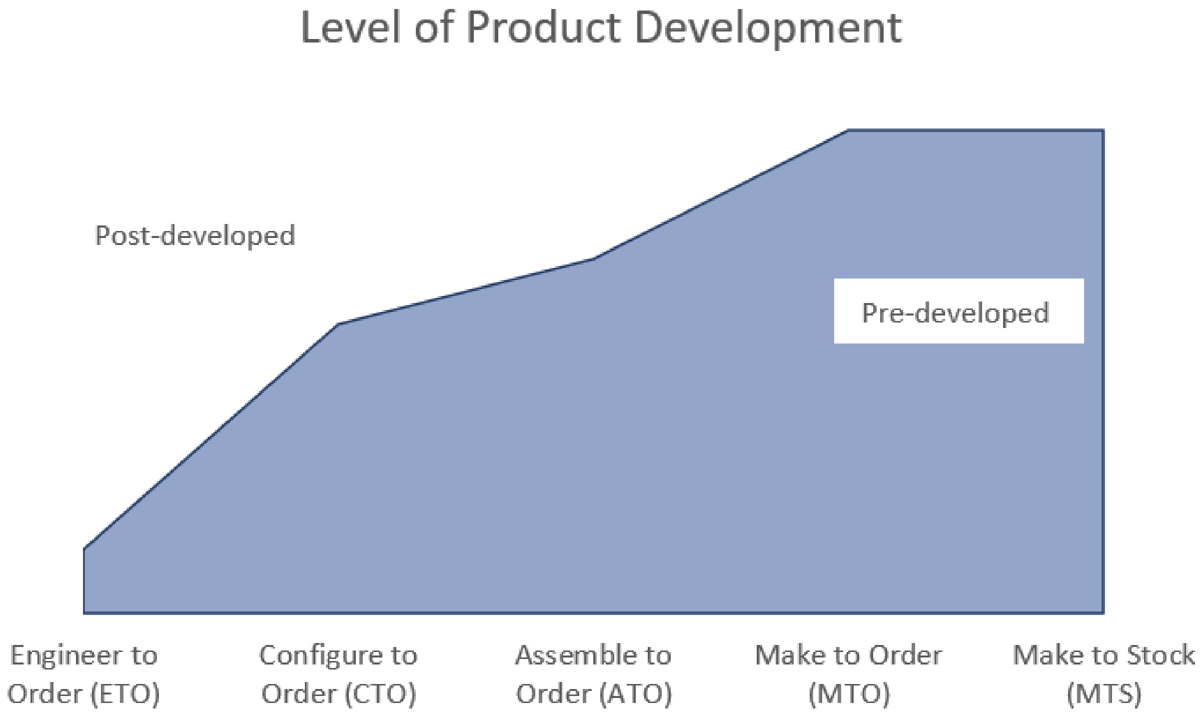

Figure 4: Customer Order Specification Decoupling Point

PRODUCT DEVELOPMENT FLOW

A new product development flow was proposed and put into practice within an offsite company in Brazil, called Company A, seeking to involve all stakeholders from the beginning of the process. The company is changing its way of creating new products, looking for more efficiency in its processes and operations.

As one of the authors works in Company A, it was possible to apply the Action Research (AR) method. The company's internal demands call for speed in changing processes, and according to O'Brien (2001), AR is suited to cases like this. It also was possible to apply multiple interactive cycles to reach the flow used, aiming to put into action all the research made on creating new products in a product platform strategy (Conte et al., 2022).

Initially, Company A didn't have a consolidated flow to develop new products, and the process was disintegrated. Figure 5 shows the proposed new product development's flow, that was created from the observation of all stakeholders involved in the process, how many times and at what moments they were involved and gave inputs in the process - it was common for an interested party to decide to change something in the product after it had already been budgeted, causing rework. Based on this, an analysis was carried out seeking to reduce the number of times that a stakeholder is involved to provide inputs, involving him only at the right moment of decision making.

The flow starts with a commercial demand – that can be a new product or a customization of an existing one - united with the constraints of the platform in which it fits. The platform is the clustering of the standard solutions that can be used, and a product with these solutions belongs to said platform. These two things are the trigger to start the development of the architectural project, which goes through evaluation by the commercial team, evaluation by the engineering team, and general evaluation in a back-and-forth cycle until it is approved by all.

With general approval, the product's CTO budget is drawn up, within a flexible spreadsheet that allows for project changes. If the cost is not approved, it goes back to the development of the architectural project. If it is approved, the process has a decoupling point, from which nothing in this product can be changed after all the necessary validations were made – *this decision-making point with no possibility of return brings more seriousness to the evaluations and avoids rework*. After that, begins the preparation of the commercial material for launch on the market, in parallel with the development of a details book that aims to identify the materials that have the most critical delivery lead time. The product remains in the portfolio until a sale takes place. With the sale and with the details book, the executive projects (e.g., complementary, production, assembly) and the final DfMA of the product are made. With all the projects ready, the final bill of materials is made, which is then passed on to the supply chain team, and this product becomes MTO.

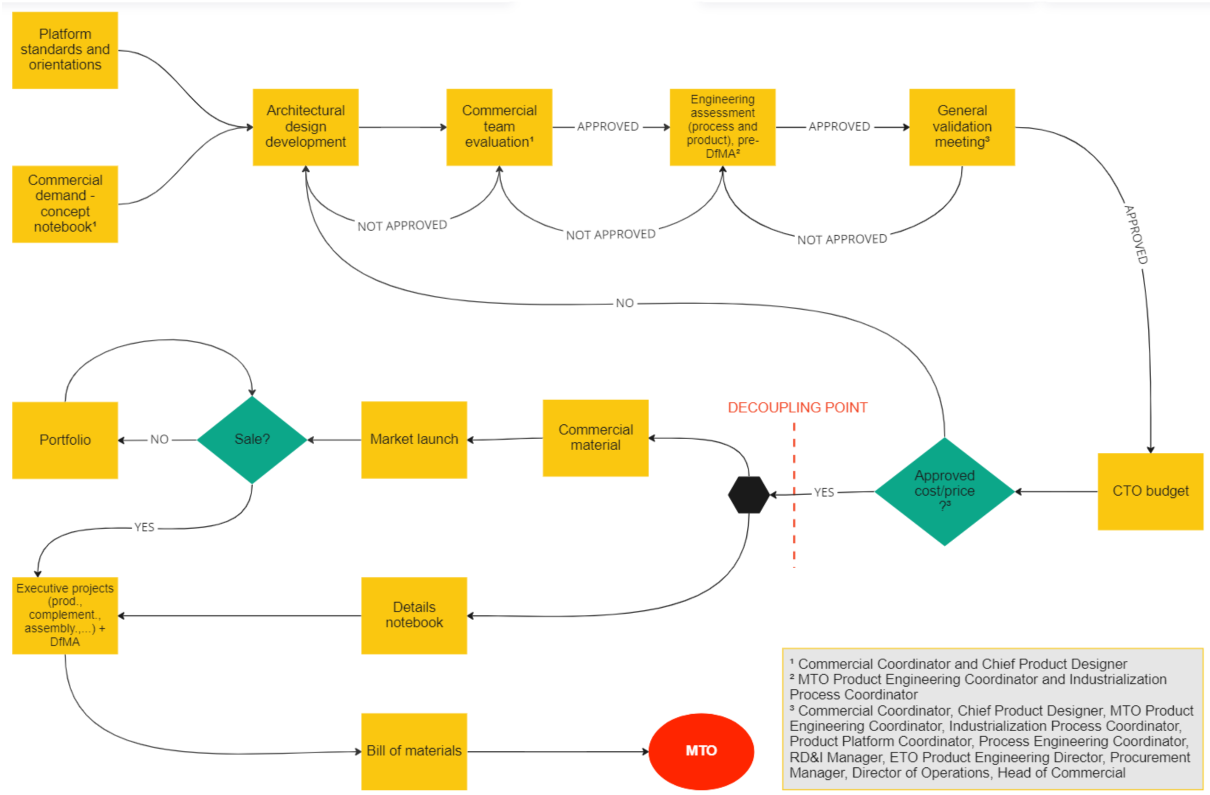

Figure 5: Integrated New Products Development's Flow

This flow takes place within any created platform, and the creation of platforms within the company takes place from the identification of needs that are not met with the existing ones, that means that if some products need solutions that are not part of an existing platform, it can be the case to create a new one based on commercial demand. For the creation of a new platform, Company A has an RD&I team that has the function of bridging the gap with the commercial team to understand new market demands, assess whether these demands can be met with existing solutions and elements or not. If not met, new solutions are studied, prototyped, evaluated and validated to become, then, a new platform.

With this flow, any changes in an already existing product can be easily and quickly met. So, if a customer wants an existing product (MTO), but with bigger rooms, or a different set of windows, for instance, he can have. His product will start as CTO and will belong to the platform characterized by the solutions and standardization used. As the solution for the company will be the same, and the client will have the desired modification, it can be said that the company has now adapted its process and caters to mass customization.

APPLICATION

The product development process shown above in Figure 5 was applied in the development of two new products in Company A, with solutions from the Single-Story House Product Platform. The demand brought by the commercial team was for two different products, Product 1 is a single-story house of approximately 50 m², and Product 2 with approximately 100 m², with the required minimum areas listed in Table 1.

Table 1: Minimum Areas for Products 1 and 2

	Product 1 (50 m²)	**Product 2 (100 m²)**
Integrated living and dining room	8.00 m²	16.00 m²
Kitchen	4.00 m²	7.00 m²
Laundry room	2.50 m² or easily adaptable to 2.50 m²	4.00 m²
Suite (bedroom + bathroom)	12.50 m²	15.00 m²
Bedroom 1	10.00 m²	10.00 m²
Bedroom 2	-	8.00 m²
Social Bathroom	2.50 m²	2.50 m²
Toilet	-	1.80 m²
Covered parking space	-	12.00 m²

For Product 1, the objective was a 15% cost reduction compared to the existing reference product. And for Product 2, the objective was a cost reduction between 10% and 15% compared to the existing reference product.

The development of the two products was carried out with integration between commercial, platform, and engineering teams, and each one took approximately 45 days for the final architectural project to be approved by all. Both products were created using solutions and standardizations previously developed from the Single-Story House Product Platform, such as bathroom modules, standard window frames, roof solution and grouping of wet cores in few hydraulic walls.

In Figure 6 it is possible to observe the base reference for Product 1 and in Figure 7 final architectural plant of Product 1.

Figure 6: 50 m² Reference Product

Figure 7: 50 m² New Product

In Figure 8 it is possible to observe the base reference for Product 2 and in Figure 9 final architectural plant of Product 2.

Figure 8: 100 m² Reference Product

Figure 9: 100 m² New Product

The application of solutions developed by Company A's RD&I team for the Single-Story House Product Platform together with the application of the new product development flow, brought about a 16.7% cost reduction in relation to the base project of 100m² house and 18.9% cost reduction in relation to the base project of the 50m² house in the estimation costs. Both results surpassed the initial target, showing the success of the strategy. When the products are executed, it will be possible to measure the savings from the predicted waste reduction, considering that the applied standard solutions are completely mastered by the operations teams, and according to the revised theory, this mastery brings waste reduction, therefore, less cost with materials (Rocha, et al., 2015 and Gibb, 2001).

DISCUSSION

It is a fact that the cost increase that has occurred in civil construction in recent years has had a negative impact on the sector. Reduction in the number of real estate launches and companies going bankrupt was the reality faced since 2019 in the Brazilian market.

As seen in the literature analysis carried out, the use of the product platform has the potential to bring more control, predictability, and sustainability to the sector. The difficulty encountered is the same as reported by Rocha et al. (2015), there are still many differences between construction and manufacturing, and although there is a growing interest in industrialization and off-site construction, they still represent a small portion of the market.

The results with the application of the integrated product development flow proposed in this study meet the results expected in the study made by Ortega et al. (2022), where every stakeholder participates in the process, bringing ideas that can optimize and make the project more efficient. Moreover, the evaluations are more decisive and with a holistic view, and that reduces the rework that exists when different stakeholders participate in different stages of the development process.

As exposed by the UK Research and Innovation & Construction Innovation Hub (2022), the major gains from using product platform strategies are primarily related to the supply chain, where the advantage lies in the standardization of raw materials, which allows for better cost control through inventory and a diversified supplier portfolio. Company A's supply chain has already benefited from the product platform strategy and has reduced the quantity of different items in their bills of materials and managed to improve negotiations by concentrating a larger volume of standard material with its suppliers. The cost reduction can revert to a more competitive price, which leads to increased sales and reaches to lower-income groups where there is a large housing deficit.

This implementation could be done with small steps - for example, a construction company/developer could always work with the same sets of frames in different projects, this allows stock and makes them less susceptible to the increase in the cost of wood and steel - and gradually increase the standardization where to find possibilities. Secondly, the advantage related to the reduction of risks, which can be the risk of accidents at work – the more an employee repeats a function, the more he masters what he does – the risk of delays, whether due to lengthy lead-times, correction of projects, labour delay, among others, and risks of rework, since in the repetition, the activity is already validated and with reduced chances of error. This is also related to the third advantage, which is the environmental one. The less rework, less waste generation, and less carbon added to activities - UK Research and Innovation & Construction Innovation Hub (2022) even calculated a process with a 70% carbon reduction using a product platform.

All these advantages were part of the gains brought with the use of the new product development flow along with the standardization solutions already existing in the company. And as the study results show, there is a significant financial gain in standardizing, integrating decision-making processes and reducing waste.

Also, with the usage of the proposed flow, it is now possible for Company A to accept some level of customization by customers, without prejudice to production and process. With the client's participation and customization, their need to renovate their homes after the construction will be reduced, as proposed by Rocha et al. (2015), which also reduces the waste generated.

In this way, we can also observe that the use of a product platform can meet the economic, social, and environmental trinity.

CONCLUSIONS

As noted, the platform strategy is best applied in manufacturing, and off-site still has a small share in the construction industry. In this way, this transition will have a potential impact on the sector, when it reaches a large portion of the market. The potential impact may be a global reduction in costs since the results of this research show a significant cost reduction in a real case.

The cost reduction obtained was possible due to the integrated product development flow, that enabled important decisions to be made in the right timing, avoiding rework. Also, it allowed designers and decision makers to calmly and concentratedly evaluate which existing solutions would bring the best gain for each product, without external interference at inopportune moments.

The process and results in this study - where it was possible to put into practice the theories to validate them in the market - are important for Company A, as they are addressing recurring problems with new solutions that can reduce aspects that are currently negative, such as the amount of waste generated and the lack of control over raw materials and labour, or the lack of customization possibilities when standards are created. The opportunity to apply all the research in a real company was essential to measure the real gains from the application of product platform strategies and to report compliance with the initial cost reduction target expected by the company. Even though it was a limitation that one of the authors works in Company A, this research was only possible because of that and supports more integration between theoretical investigations and practical applications. Another limitation found is that the company started recently to apply and focus in product platform strategies. In a company that has their product platform consolidated, other gains not even approached in this study may be possible – such as standardization of processes in the production line. And the last limitation found in this case-study, is that the gains from waste reduction are not measurable in the project phase, only in the execution, therefore, this specific gain remains theoretical.

For the most part, the literature found is related to sectors other than civil construction, which indicates a large space for research and development.

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COLLABORATION IN THE DETAILED DESIGN PHASE OF CONSTRUCTION PROJECTS – A STUDY OF INTERDISCIPLINARY TEAMS

Mona Salam[1], Perry Forsythe[2], and Catherine Killen[3]

ABSTRACT

Collaboration in construction projects has become a primary requirement in common delivery methods, especially in the detailed design phase to achieve value for the client. The involvement of multiple organisations, such as the client, architects, design consultants, project managers, contractors, and subcontractors, increases the complexity of implementing successful collaboration. Recent studies have focused on the financial aspect of collaboration but undervalued the social dimension which reflects behavioural actions that can lead to goal misalignment. There is less known about the highly dynamic nature of collaboration at a project level between participants with different views, objectives, and working practices. Through a study of two interdisciplinary teams in the detailed design phase of large-scale construction projects, participants' perceptions of collaboration were analysed to reveal that participants have different ways of viewing their collaboration, ranging from facilitation factors, working processes, and outcomes. The study advances the theory of collaboration in design management by adopting an inter-organisational practice-based perspective to assess collaboration. The findings suggest a more tailored management approach based on understanding the processes and outcomes and regular monitoring of the behaviour actions for collaboration to succeed.

KEYWORDS

Collaboration, interdisciplinary teams, design management, early contractor involvement

INTRODUCTION

Collaboration in large-scale construction projects is challenging due to the presence of multiple organisations and skilled professionals representing the client, architects, design consultants, project managers, contractors, and subcontractors forming interdisciplinary teams (Emmitt 2010; Winch 2009). Although these participants have different backgrounds, goals, and preferred working practices that affect their discussions and methods of resolving conflicts, they are required to work closely as a cohesive team to improve value for the client (Baiden, Price & Dainty 2006). In common delivery methods such as design and build and managing contractor, the detailed design phase involves several design reviews and evaluations between designers and contractors to finalise design decisions and the associated cost, which requires a good understanding of the interdependent relations between these actors (Kalsaas, Rullestad & Thorud 2020).

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In large-scale construction projects, the finalisation of design documents during the detailed design phase can take more than a year, creating challenges for participants to maintain their collaboration efforts and exchange information and technical knowledge constructively (Walker, Davis & Stevenson 2017). Recent research on the detailed design phase revealed designers' concerns about delays and late changes when finalising designs due to the uncertainty of receiving feedback from the contractors in a timely fashion (Kalsaas, Rullestad & Thorud 2020). Further, late design changes in the design phase are the leading cause of rework in the construction phase, according to research showing that the average cost of design changes was up to 14.2% of the construction cost (Lopez & Love 2011). A such, managing interdisciplinary teams in the detailed design phase is particularly challenging as the contractors' focus shifts to cost and scheduling to finalise design documentation, which conflicts with the iterative nature of architects' work (Forbes & Ahmed 2010). These differences in working practices are reflected in design documents that may be incomplete and not precise enough for the subsequent disciplines in the supply chain (Ballard et al. 2007; O'Connor James & Koo Hyun 2020; Tzortzopoulos, Kagioglou & Koskela 2020).

Successful traits of collaboration in multi-party projects included sharing risk and reward models and aligning financial interests (Walker & Lloyd-Walker 2020). These traits tend to focus on the financial aspect of collaboration and undervalue the social dimension reflected in behavioural actions that can lead to goal misalignment and miscommunication among interdisciplinary teams (Manata et al. 2020; Suprapto, Bakker & Mooi 2015). Understanding the highly dynamic nature of collaboration is therefore important at a project level where interdisciplinary teams include different personalities, objectives, and working practices (Bresnen & Marshall 2002; Eriksson & Westerberg 2011).

Given these insights, this paper presents an empirical investigation on collaboration as a perception-based phenomenon to understand how participants perceive and evaluate their collaboration and the impacts on their working practices in detailed design meetings of large-scale construction projects in Australia. It draws upon the inter-organisational theory that differentiates between antecedents of collaboration, processes, and outcomes and pays special attention to the subjectivity aspect of collaboration (Gray 1989; Gray & Purdy 2018; Huxham & Vangen 2013) to study the research question*: How can team members' perceptions of collaboration in the detailed design meetings of construction projects provide insights into improving interdisciplinary collaboration?*

LITERATURE REVIEW

Interdisciplinary collaboration is considered a solution to persistent issues in large-scale construction projects, such as adversarial relationships, poor communication, schedule and budget overruns and high uncertainty (Deep, Gajendran & Jefferies 2020; Walker, Davis & Stevenson 2017). Successful collaborative practices that rely on multi-party contracting frameworks have demonstrated an ability to control cost and improve performance in construction projects. However, recent studies have reported practical problems such as lack of commitment, inefficient communication, sharing limited financial information, conflicting personalities, and lack of team building activities and workshops to rectify goal misalignment (Koolwijk et al. 2018; Manata et al. 2020). Contracting frameworks are not considered sufficient to shift participants' mindsets to a fully collaborative one in large-scale construction projects due to the gap between agreements at the formal organisation level and what happens at the project team level (Bresnen & Marshall 2002; Suprapto, Bakker & Mooi 2015).

From an inter-organisational perspective, collaboration is defined "as the process through which parties who see different aspects of a problem can constructively explore their differences and search for solutions that go beyond their limited vision of what is possible"(Gray 1989, p. 5). This definition is adopted for this research, as it focusses on the interactive process of interdisciplinary collaboration and recognises that participants have different backgrounds, which aligns with this research. However, the integration of knowledge and experience in design and construction to collaboratively solve complex problems in construction projects needs some clarification.

Interdisciplinary collaboration has been discussed extensively in the lean construction literature to cope with uncertainty, reduce process waste and improve workflow to deliver value to the client by using tools that follow structured methods and procedures (ex.Ballard et al. 2007; Pedó et al. 2022; Tzortzopoulos, Kagioglou & Koskela 2020). The formation of an interdisciplinary team at the outset of the project is a fundamental aspect to improve the design processes and reduce constructability problems (Nguyen, Lostuvali & Tommelein 2009; Raviv, Shapira & Sacks 2022).

In the design phase of construction projects, set-based design (SBD) approach integrates construction expertise into the process of selecting design solutions to align viewpoints regarding design concepts from the start of the design phase to reduce negative design iteration (Parrish et al. 2008). Another useful method is the Choosing by Advantages (CBA) which is a structured approach of multi-criteria that prioritises the importance of advantages when making decisions by integrating construction knowledge into the design decision-making process (Schöttle, Arroyo & Christensen 2020).

Lean construction tools also focus on cost control in the design phase by integrating design and construction knowledge through the adoption of the target value design (TVD) concept. The TVD approach encompasses various lean methodologies and tools such as SBD, co-location of the project team in a common space, and expands to address constructability issues (Nguyen, Lostuvali & Tommelein 2009; Smoge, Torp & Johansen 2020). The TVD concept allows interdisciplinary teams to collectively manage and control target cost by moving money across trade packages to optimise the project as a whole (Ballard & Pennanen 2013).

The interactive process of interdisciplinary teams was also examined in the integrated project delivery (IPD) approach that operates at the project level by integrating design and construction teams, working practices and the business structures of organisations involved in a construction project (El Asmar 2012). The IPD method is an adaption of the Australian project alliancing approach, which shares a similar project delivery approach and has been commonly used in the infrastructure projects (Walker & Lloyd-Walker 2020). Research on the collaborative working environment in IPD projects has focused on identifying features of integrated teams, such as sharing information, defined roles and responsibilities, co-location, and trust in expertise (Abdirad & Pishdad-Bozorgi 2014; Baiden, Price & Dainty 2006; El Asmar, Hanna & Loh 2013).

Collaboration traits of interdisciplinary teams can be categorised into antecedents, interactive processes and outcomes (Salam, Forsythe & Killen 2019). These traits are 1) antecedents such as defining roles and responsibilities, having a common goal, co-locating the team in a common place, and a common means of sharing information, 2) interactive process traits including interactive coordination, collective decision making, and aligning cost interests, 3) outcomes traits include achieving value for the client, cost and time efficiencies, and trust in expertise. The interactive process has the least traits and still needs some clarification.

To advance the discussion on the interactive process in construction projects involving multiple organisations and skilled professionals, the role of the inter-organisational theoretical approach is discussed next to gain a deeper understanding of what conceptually constitutes interdisciplinary collaboration processes in the detailed design phase of construction projects.

THEORETICAL BACKGROUND

Theoretically, the inter-organisational practice-based stream differentiates between antecedents, processes, and outcomes of collaboration (Gray 1989; Gray & Purdy 2018; Huxham & Vangen 2013; Thomson & Perry 2006). Gray's (1989) collaboration model focuses on processes and outcomes, and advocates that collaboration efforts proceed linearly: 1) problem setting, 2) direction setting and 3) objective and 4) subjective outcomes.

In the *problem setting* phase, participants define the problem by performing a detailed analysis to develop a common understanding of each other's concerns. They then proceed to the *direction setting* phase where they refine the solutions and agree collectively on the best solution that satisfies their technical concerns. *Objective* measures are then used to document the implementation of the solution while *subjective* measures monitor participants' satisfaction with the results achieved (Gray 1989; Gray & Purdy 2018). The inter-organisational practice-based stream also recognises the long-term nature of the collaboration process (Gray 1989; Gray & Purdy 2018). As Gray notes, "respect for differences is an easy virtue to champion verbally and much more difficult to put in practice in our day-to-day affairs" (1989, p. 11). In conflicting situations, participants tend to forget that their underlying concerns are primarily intertwined and that their interdependence is much needed to solve complex problems (Gray 1989; Gray & Purdy 2018).

These inter-organisational concepts align with the practices of participants in the detailed design phase of large-scale construction projects due to the long duration, where conflicts are expected to occur between designers and contractors due to the inherent differences in their working practices and procedures (Eynon 2013). These circumstances put designers and contractors under continuous pressure in the detailed design phase to achieve the design objectives within the project time and budget constraints, which might influence participants' perception of their collaboration efforts (Winch 2009). Building on the perspectives of the inter-organisational theory to conceptualise collaboration, this study is expected to contribute to our understanding of project team dynamics in the AEC industry. Moreover, the study of the perceptions of participants about their collaboration in large-scale construction projects can help managers and professionals recognise and monitor the working process, foresee the impacts on the outcomes and potentially take actions to improve performance.

METHOD

To better understand collaboration as a perception-based phenomenon and how participants perceive their collaboration and the impacts on their working practices, the study collected collaboration scores in detailed design meetings of two large-scale construction projects in Australia followed by interviews. The research design adopted a longitudinal case study approach utilising replication logic (Yin 2017) to explore interdisciplinary collaboration in the detailed design phase of two contrasting case studies having different design environments. The two case studies were part of the same overarching educational building project and in methodological terms, this aimed to help minimise the effects of intervening variables such as different contract types, means of sharing information, and location and building type. The selection of the case study was based on (i) the case had enough stakeholders representing the client, architect, design consultant, main contractor, and subcontractor to form the interdisciplinary team, and (ii) the case represented a different degree of design complexity to reflect the contrasting design environments.

The chosen overarching educational building project included a five-storey podium (case study B), and a 10-storey tower (case study A). Case study A involved a relatively standard façade design, which used a closed-cavity façade (CCF) system developed by the subcontractor firm and demonstrated fewer design challenges due to the extensive knowledge of the subcontractor about the facade components. Case study B involved a bespoke façade type that created several challenges related to the design of the supporting structural system. These cases were treated as two separate work packages in terms of subcontractors' firms and budgets. Representatives of the client, main contractor, architects, and façade consultant were the same for both case studies. The different participants were the subcontractors' representatives assigned to each façade package.

DATA COLLECTION AND ANALYSIS

A simple perception-based method was used to capture the collaboration rating of the participants after each meeting over a year to cover the detailed design phase. Each firm assigned a key participant as the point of contact for the projects. These key participants were involved in the data collection method and were asked to rate their collaboration experience after each meeting using a Likert (1932) scale level of quality of 1–9, where 1 is very poor, 5 is neutral, and 9 is excellent. The perception question was emailed to each key participant shortly after the meeting to make sure that participants rated their collaboration very soon after the meeting to capture their emotive thoughts as well as objective outcomes. The survey question was: *Can you please rate your collaboration experience in [insert trade package name] meeting [insert date] using a scale of 1 to 9 (where 1=very poor, 5=neutral, 9=excellent)?* A total of 215 collaborating ratings were collected. The ratings were analysed following a systematic approach using quantitative statistical results to direct the next step in data collection.

The perception measure was followed by targeted interviews focused specifically on participants who gave contrasting collaboration scores from the same meeting. These interviews included an open question asking for the reasons behind their extremely low or high collaboration ratings. A total of 34 interviews were conducted and analysed using pattern matching (Miles, Huberman & Saldana 2014), where the codes were categorised and grouped according to the antecedents of collaboration and the four phases of Gray's (1989) collaboration model discussed above.

FINDINGS

The client procured the overarching project as a managing contractor with a cost-plus contract. Another set of separate consulting contracts existed between the client and the architectural firm and the façade consulting firm. The main contractor had a separate design, construct and maintenance contract with each of the subcontractor firms. Although this procurement setting has a traditional essence, it was found suitable for this study as the proposed collaborative environment is imperative in the detailed design phase to achieve value for the client (Koolwijk et al. 2018). In addition, the integrated business model used in the multi-party contractual setting is still limited in commercial construction projects in Australia (Rankohi, Bourgault & Iordanova 2022).

CASE STUDY A

The detailed design phase for case study A included 21 meetings and a total of 100 collaboration scores collected after each meeting. Key participants involved in the data collection (ratings and interviews) were the client's delivery manager (L1), the main contractor's project engineer (C1), the architectural firm's senior architect (R2), the façade consultant (F1) and the subcontractor's senior project manager (T2) for case study A. Figure 1 below, collaboration scores for case study A are presented on the y-axis in the 21 meetings (shown as Mtg) on the x-axis.

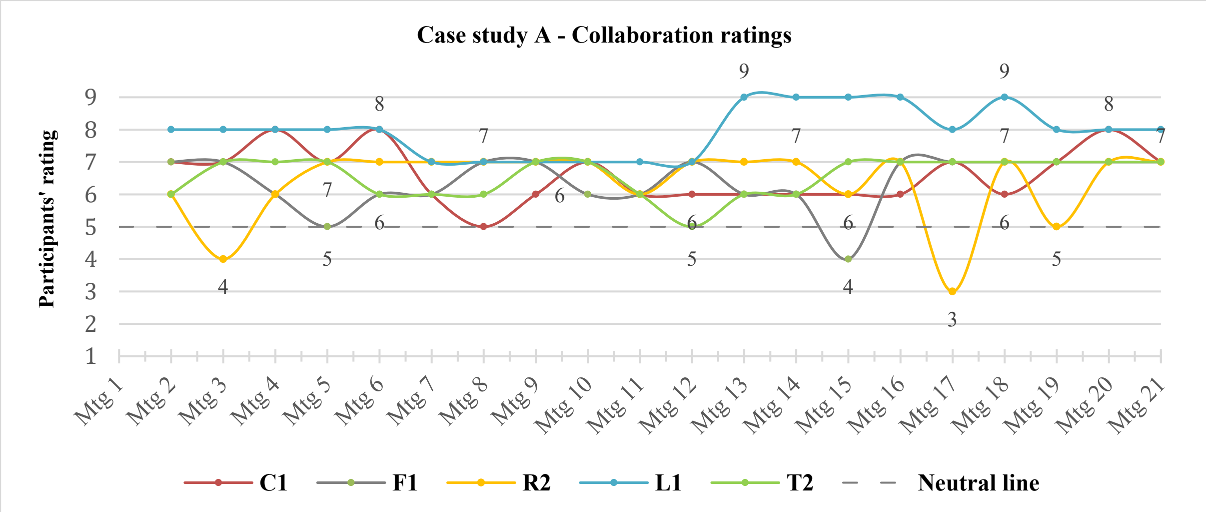

Figure 1: Case study A – Collaboration ratings by meeting

Analysis of the ratings revealed that there was no consensus among participants about their collaborative experiences, as the ratings did not align at any meeting. The most common ratings were 7 (50%) and 6 (26%). Most of the ratings were in the positive part of the graph above the score of 5, and only three ratings were below the neutral line. The client (L1) believed that collaboration was excellent (rating 9) in meetings 13, 14, 15, 16 and 18. The client was assured that the subcontractor firm could accommodate the design requirements and match the architects' vision, given that they developed the closed cavity façade CCF system as explained in a targeted interview: *"The process is positive because they know their system; they are looking at winter gardens, glass curves and everything. The meetings are generally positive" [L1, rating for meeting 6].* The constant satisfaction with the collaborative environment in the meetings was also seen in the subcontractor (T2) ratings which did not change much as the majority were 6 or 7. Subsequent interviews revealed that the subcontractor's senior project manager rated collaboration positively due to the team formation, including the designers and client. The formation of such an interdisciplinary team allowed the subcontractor to get instant feedback on the proposed design solutions from the designers and the client's approvals as quoted: *"Because the meetings are mainly related to the facade. So, it wasn't just a normal meeting that has everybody else on the project in the meeting, but for the façade to have an understanding of the design" [T2, rating of 6 & 7 for meetings 8 and 9].*

A different view of the collaboration experience was seen in the ratings of the main contractor (C1), architect (R2) and façade consultant (F1) which fluctuated between a high of 8 and a low of 3. For instance, the senior architect (R2) gave a low score of 4 in meeting 3 indicating an early sign of dissatisfaction. In the early meetings of the detailed design phase, the discussions included the scope register, information about façade components and their costs, and explanations about the façade system and how it works. The architects were concerned about whether the subcontractor had fully understood the design intent before approving the scope as quoted in the interview: *"I guess it is a complex façade stepping in stepping out, twisting... it is a closed cavity façade system and there is a lot of sort of services and extra constraints along with that façade type...it is just more complex than a traditional façade type" [R2, rating of 4 for meeting 3].*

Despite the above two low ratings of collaboration experience, the senior architect (R2) showed satisfaction with the working experience because of the subcontractors' continuous detailed feedback given in the meetings about the proposed design options, including dimensions, manufacturing process, installation processes and tolerance needed for the construction crew to secure connections, and cost breakdown. These thorough explanations including the cost associated with each design component informed the designers about which part of the design was expensive thus they could choose the best design solution that satisfied both practicality and cost as quoted: "*They gave us how much it costs; they break it up for us, it is easy to see if we make this decision, it will cost this much money" [R2, rating of 7 for meeting 8]. "They are really receptive towards our idea; they do not just say no and don't back it up with any sort of information… they seem to take on board what we want… giving us choices" [R2, rating of 7 for meeting 18].*

The contractor's project engineer (C1) had constant positive collaboration ratings above the neutral line. However, the ratings decreased from 7 in meeting 10 to 6 in meetings 11 and 12 due to excessive design reviews and coordination actions. Some of the minor design tasks required investigation including design options, cost analysis, and seeking the client's approval which generated several coordination tasks to gather and disseminate information and was rejected later due to cost overrun causing dissatisfaction to the main contractor (C1) quoted in the interview: *"I sent many correspondences between meetings outlining everything fully, it takes me a lot of time to outline the history, the marked-up drawings, and this is option A and this option B, but no response" [C1, rating of 6 for meeting 12].*

CASE STUDY B

The detailed design phase for case study B included 24 detailed design meetings where 115 collaboration scores were collected after each meeting. The key participants involved in the data collection (ratings and interviews) were the client's delivery manager (L1), the main contractor's project engineer (C1), the architectural firm's senior architect (R2), the façade consultant (F1) and the subcontractor's project manager (P3). Figure 2 below, collaboration scores for case study B are presented on the y-axis in the 24 meetings (shown as Mtg) on the x-axis.

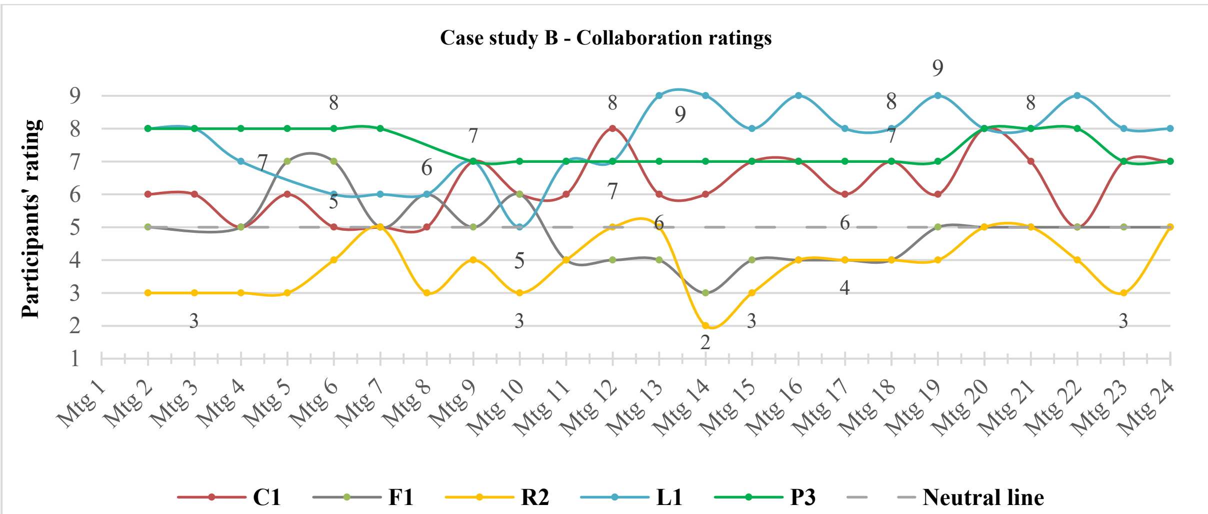

Figure 2: Case study B – Collaboration ratings by meeting

The observation of no consensus among participants about their collaborative experiences existed also in case study B due to the significant divergence between the ratings. Participants' ratings were widely scattered across the neutral line (rating of 5 points), with the most frequent ratings being 7 (22%), 8 (19%) and 5 (17%). For example, all architect ratings (R2) were below the neutral line, indicating a continuous dissatisfaction with the collaborative experience. In early meetings, the scope of the design was not clear due to the discrepancy in the design documentation, as participants had different versions of the tender documents. Thus, the proposed design solution did not match the design intent, which led to led to confrontation discussions, design changes to match the design intent, and delays in developing the design as quoted in the subsequent interview: *"They (subcontractors) don't seem to be listening to our views, like how many times we explained our view on the lower connection of reading rooms, we removed the louvres and its structure, but they keep asking or acting as if it is still there, it's frustrating" [R2, rating of 3 for meeting 5].*

A slightly different rating pattern is seen in the facade consultant ratings (F1) because the ratings were above the neutral line at the initial meetings and then continue to be below the neutral line (rating of 5 points) indicating dissatisfaction at many meetings. The façade consultant was also confused about the scope of the design due to its impact on the structural system design as quoted in the interview: *"The scope, yea, if everyone was clear on that it would be much simpler; we will know who is doing what… but that's taken us since April basically till now (July) to understand that because no one declared it openly… I keep asking questions and every time I ask a question; I find something new" [F1, rating of 5 for meeting 7].* Furthermore, both the architects and the façade consultant were concerned about the insufficient fundamental information on the structural system given in the meetings, but the subcontractor preferred not to go into detailed engineering calculations before agreeing on the design principles. These conflicting views created confrontation in the design discussions because the designers were trying to work out a practical design solution with the subcontractor as F1 quoted: *"They (subcontractor) don't want to say too much because the more you say the more you get feedback on… once they engaged the steel contractor, they will progress their shop drawings, which means that the steel guy would start his shop drawings and will have a note on his drawing that says need to confirm connection if they didn't tell us what that is beforehand" [F1, rating of 3 for meeting 14].*

The contractor project engineer (C1) had constant positive collaboration scores above the neutral line. However, the scores were closer to the natural line in the first 8 meetings, as he had a different view of the changes in the design scope due to budget limits as quoted: *'It is not as per their [referring to the architects] drawings, but we had to let it be based on something because if we were behind, and we would not have a building" [C1, rating of 5 for meeting 4].'* The process of refining the design continued to occur to investigate other ways to reduce the cost, which required further design changes and consequently more reviews. The main contractor (C1) was dissatisfied with these excessive reviews because the design was not progressing as scheduled as quoted: *"We just got 12 very different façade types that have constantly changed, we should be sticking to the design not just keep changing and changing… we don't know where the beam is and it is still changing, today the wind beam is changed again!" [C1, rating of 5 for meeting 8].*

The client's (L1) ratings were positive in general with all ratings above the neutral line showing an overall satisfaction with the collaborative experience despite the tough discussions between designers and contractors in the meetings as quoted in the subsequent interview: *"I gave a rate of 7 because at the end they [referring to the subcontractor] agreed to look at the design again and that is what matters to me" [L1, rating of 7 for meeting 4].*

Despite the design challenges, the subcontractor's (P3) ratings were also positive throughout the meetings at 7 or 8 indicating continuous satisfaction with the collaboration experience due to the concept of early participation in design decisions and being part of the team, as quoted in the interview: "*Yea, my ratings were much higher because we had a lot of coordination on something like this, where in previous projects many decisions were already made before we got involved so we also do not have a say in deciding how the project progresses" [P3, rating of 8 for meeting 5].*

As negotiations and consistent disagreement between participants continued to occur, an organisational decision involving the client and the main contractor was taken after meeting 8 including changing some of the meetings to be a design workshop as a mitigation plan for the delays encountered. A total of six design-focused workshops were held to replace weekly meetings 9, 11, 12, 16, 18 and 19 to better understand the technical concerns directly from the subcontractor's staff who were documenting the design drawings. The collaboration ratings of the participants began to be somewhat consistent after these workshops because the subcontractor team gave detailed feedback that made architects more informed about design restrictions and offered proper design solutions at the meetings, as quoted by the architect and the principal contractor: *'The workshops definitely are more constructive because it is much easier to get things done and decisions made and to work through details rather than having a formal meeting atmosphere and going through a lot of stuff that is not always super critical to what we are doing at the moment' [R2, rating of 5 for meeting 13]. "The workshops are more collaborative … generally because the group is not as big… plus the actual draftsmen work and try and get this resolved sort of coming with real problems and architects a bit more receptive and get things to work" [C1, rating of 8 for meeting 12].*

DISCUSSION

To address the research question, the study found that participants had different views of their collaboration and focused on different phases of collaboration when explaining their ratings. The client prioritised outcomes, subcontractors focused on antecedents, and the main contractor, architects, and facade consultant focused on processes. In the bespoke design case study, there was a greater variance in ratings, with dissatisfaction expressed by those focused on the collaboration's processes.

The client's delivery manager (L1) rated collaboration based on the outcomes achieved rather than the processes in both case studies. The findings support the study conducted by Tzortzopoulos, Kagioglou & Koskela (2020) which highlighted the client's concerns about preserving value during the handover of design responsibilities from architects to subcontractors. In both case studies, the subcontractors expressed satisfaction with their collaboration experience, albeit for different reasons tied to team formation and early involvement in design decision-making. These results are consistent with the existing lean construction literature, which recommends involving subcontractors early on in the design process to provide constructability feedback, enabling designers to make well-informed decisions regarding proposed solutions (Denerolle 2013; Raviv, Shapira & Sacks 2022). Despite the fact that the subcontractors displayed behaviours associated with providing constructability feedback, both attributed their high collaboration ratings to collaboration antecedents. There could be a couple of potential reasons for such practices. Firstly, it is plausible that the subcontractors may not be accustomed to expressing their views on actual working practices. Secondly, the lack of managerial attention towards cultivating a fair working environment where all participants have an equal opportunity to voice their opinions on working practices could be a contributing factor. (Eynon 2013; Winch 2009).

The interviews revealed that the R2, F1, and C1 scores were more focused on the collaboration processes than the outcomes. The high collaboration scores of the senior architect (R2) were related to elaborate feedback backed up by a breakdown of the cost of the design components. These practices led to adopting of practical design solutions and elevating the sense of mutual accountability where all participants shared the responsibility of meeting the design deliverables timeframe. Aligned with Dietrich et al. (2010), these findings provide insights into the knowledge creation process (interaction activities of feedback, brainstorming, and innovation) that are specific to the design discussions. The findings also support Denerolle's (2013) approach of fostering interdisciplinary collaboration through weekly meetings. Although design refinements are common in construction projects due to the highly iterative nature of the design process (Eynon 2013), they were seen by C1 as unnecessary coordination tasks which align with the well-established lean concept of process waste in the design phase that needs to be minimised (Tzortzopoulos, Kagioglou & Koskela 2020). These findings support the need for a planning management approach that is capable of handling the normal design changes in the detailed design phase (Kalsaas, Rullestad & Thorud 2020).

Practices associated with low ratings emerged in case study B because of the dissatisfaction of the architects (R2) and façade consultant (F1) with the practices of lack of transparency and providing inadequate design information combined with minimal cost justification which resulted in a call for mitigation actions to reduce confrontation. These findings demonstrate how goal misalignment at initial meetings led to unhealthy communication behaviours and poor decision quality (Manata et al. 2020; Suprapto, Bakker & Mooi 2015). Although Suprapto et al. (2015) point to the lack of willingness of senior management to be involved in improving team building and interpersonal relationships between participants at the project level, the findings of this study do not support this view, as the workshop decision was made by the senior representative of the client (L1). The diversity of participants involved in the detailed design meetings resulted in different interpretations or ways to frame the problems that existed in their discussions. The inter-organisational practice-based perspective explains such situations of participants failing to align their views and reaching a frame break stage (Gray 1989) , where the problems at the micro level were amplified in scope and time at the macro level (cross-organisational level) (Gray & Purdy 2018). This led to seeking mitigation actions to ease the tension between participants and reduce confrontation and avoid further problems associated with variations or claims for delay in construction projects (Walker, Davis & Stevenson 2017).

These findings suggest that collaboration needs a more tailored management approach based on understanding collaboration as a process that leads to outcomes, and requires regular monitoring of behavioural actions and differing frames when a problem occurs. Managers could remind participants that different interpretations of a problem do not mean by definition that they are opposing views and that their underlying concerns are initially intertwined and need their interdependence to solve the problem (Gray 1989; Gray & Purdy 2018). These different frames of the same problem can enhance creativity and innovation if well managed. More importantly, if participants began to lose their momentum, interventions can be introduced to address the reasons for collaboration inertia and help participants restore their efforts.

CONCLUSION

This paper examines collaboration as a perception-based phenomenon based on the opinions of participants on their collaboration at design meetings of construction projects. Analysis of the ratings of the participants reveals differences in the ways in which people from different organisations viewed collaboration. Two collaboration paths were identified from the analysis of ratings and interviews. A smooth path was achieved through detailed feedback to raise the awareness of technical constraints and sharing cost information to collectively make informed design decisions. The lack of transparency and inadequate design information led to a disruptive collaboration path. The practices of differing frames for addressing technical problems were resolved by an intervention to improve collaboration performance. Theoretically, the findings contribute to the growing literature on the need for better interdisciplinary collaboration in the construction industry to improve performance and provide useful insights into design management. Adopting the inter-organisational perspective provides a new lens to analyse interdisciplinary collaboration perceptions and reveal the practices that influence collaboration practices in construction projects, which can be further explored in future research.

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IMPROVING PRODUCTIVITY IN VENTILATION AND PLUMBING INSTALLATIONS BY DEVELOPING DESIGNS

Tuomas Valkonen[1] and Olli Seppänen[2]

ABSTRACT

Quality of designs is one of the most important factors impacting the productivity of mechanical, electrical, and plumbing work. Previous research does not investigate problems with design in detail. This research aimed to identify design aspects where additional investments in design would increase productivity in installation. For this purpose, we selected three construction sites to identify deviations from designs, and interview installers on identified deviations and buildability in general. Observed deviations were divided into three main categories based on the cause of deviation: insufficient space reservations, missing model components, and buildability. Based on our findings we suggest five methods for developing designing: 1. BIM should be used in designing. 2. BIM coordination should include the assessment of buildability. 3. Better use of BIM requires high level of detail and high accuracy in all design models. 4. Contractors knowledge on buildability, schedule, and order of installation should be utilized in designing. 5. Optimizing material cost should be part of designing.

KEYWORDS

BIM, collaboration, assembly, HVAC, design

INTRODUCTION

The main purpose of designs is to convey the designers' intent to construction and enable fabrication of functioning buildings. Ideal designs for construction would contain everything that needs to be installed and they could be executed precisely, meaning that there would be no need for improvisation on site. Unclear designs lead to improvisation and improvisation leads to low productivity (Johnston and Brennan, 1996). Design quality and coordination was identified as the second most important issue affecting productivity concerning mechanical, electrical, and plumbing (MEP) installations in a study by Seppänen & Görsch (2022). The study estimated the potential production improvement to be 20 % by improving design quality and coordination. Similarly Wu et al. (2022) specified clash detection, network optimization, and construction simulation as methods to improve MEP installation productivity.

Prefabrication requires accurate designs that can be executed exactly and utilised as part of assemblies; designs for prefabrication can be considered examples of ideal designs. A study by Poirier et al. (2015) suggested that using high level of detail in BIM and designing for prefabrication might have significant potential for increasing productivity in MEP work. High level of detail enables effective work planning and is a precursor to using prefabrication (Song et al., 2017; Lavikka et al., 2021). High level of detail also refers to geometric representation

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and model accuracy. Lavikka et al. (2021) also found that current design quality in Finland is not sufficient for prefabrication. This is one key reason why prefabrication of MEP has not been widely adopted in the Finnish construction market.

Designing for prefabrication is characterised by buildability of designs. Buildability can be considered as tool or methodology throughout the project. In this study we focus on design and construction phases and define buildability as designers using construction knowledge to draft designs that facilitate efficient building of systems or parts of them (Wimalaratne et al., 2021). Designs where buildability is not considered, such as models with clashes, cause waste and rework in construction.

Building information modelling (BIM) and coordination of design models can be used for ensuring buildability across disciplines. Clashes in MEP design models have been studied to identify their root causes and frameworks for resolving them (Tommelein & Gholami, 2012; Wang & Leite, 2016; Chauhan et al., 2022). Tommelein and Gholami (2012) suggested classifications for three different types of clashes, investigated their root causes, and ultimately concluded that clashes highly relate to buildability of designs. Effective coordination of BIM and using virtual design and construction technologies have been shown to increase productivity significantly (Khanzode et al., 2008). Past studies have been covering widely different frameworks and their productivity in BIM coordination (Lee & Kim, 2014; Seo et al., 2012; Korman et al., 2008; Korman & Tatum, 2006; Korman et al., 2003), but are limited to solving clashes that are visible in the models. Wang et al (2016) suggested a framework for MEP clash detection and resolution, their study reported 51 identified design errors from construction site but did not specify the types of errors or how they could have been avoided in designing.

While studies show that BIM coordination increases productivity (Wu et al., 2022; Khanzode et al., 2008), and BIM is widely used, there are also studies showing that current practices cause waste, and problems in coordination process remain (Seppänen & Görsch, 2022; Chauhan et al., 2022). This raises the question of what causes the need for improvisation and rework in MEP installations regardless of BIM use, clash detection, and coordination. To our knowledge there are no studies documenting reasons for deviating from designs and how these deviations relate to designing. The aim of this study is to identify these remaining problems and to suggest improvements to design process for eliminating these problems. Our aim is related to the key lean principle of minimizing waste, with focus on construction and improving designs. For this purpose we conducted three case studies on construction sites to document problems installers are dealing with.

METHODS

Based on the previous research we know that installers use significant amount of time for designing installations on site. The aim of this study was to document deviations from designs, determine causes for these deviations, and discuss possible solutions for removing these issues. To document issues in MEP designing we studied deviations in installation on three construction sites. The sites were selected to represent different project and building types. Key aspects of studied projects are shown in Table 1. All three projects had different designers, MEP contractors and main contractors. Installations of MEP systems were ongoing and observable in all selected sites.

The research was carried out in spring 2022. The first author was on-site observing installations and interviewing installers. A deviation was defined as any installation that was not identical to designs. Examples of deviations included using different parts or installing in different locations. Deviation in this context does not mean that the systems would not work as intended. Some of the deviations can result in non-functioning systems and others do not. The first author compared installations to designs and reported differences between as-designed and as-built. The identified deviations were documented by photographing the installation and writing notes about the reasons leading to the changes. The reasons were determined by interviewing installers and observing conditions affecting the installation. The installers were also interviewed regarding design issues in general and suggestions for improving designs.

All three case sites were different from one another. Cases 1 and 2 were new constructions where the first case was a school building and the second case was an apartment building. Case 3 was a renovation project in a school building where only the old structure was left untouched. All cases used BIM but there was significant variation in the utility and quality of the models. BIM was best used in Case 2 where design models were most detailed and coordinated to eliminate collisions. Lowest use of BIM was in Case 3 where a design model existed only for ventilation systems and BIM was not used in installation. Case 1 had design models of all disciplines and models were partially coordinated however there were obvious issues left unresolved. Installers of Case 1 used 2D drawings while they had seen the BIM model in meetings. Latest BIM models and 2D designs were used for evaluating installations on site. Prefabrication was not used in any of the studied installations.

Table 1: Characteristics of studied projects.

	Building type	Construction type	BIM used in designing	BIM used in construction
Case 1	Residential building	New Construction	Yes	Partially
Case 2	Educational building	New Construction	Yes	Yes
Case 3	Educational building	Renovation	Partially	No

RESULTS

Differences between design and installation were frequent on the studied construction sites. All studied spaces showed some examples of improvisation by installers. However, there were distinct differences of observed issue types between building and project types. Overall, the use of BIM in designing and installation changed problem types and higher utilisation of BIM decreased the number and severity of problems. Based on the results, BIM practices in case projects were not sufficient to remove all the problems and many issues were still left for installers to solve.

The identified problems can be divided into three main categories: insufficient space reservations, missing model components, and buildability. All these problem types could be found on all three cases. Insufficient space reservations were predominant in Case 3 which can be attributed to renovation project type. Missing model components, such as hangers or structural elements, caused issues in all cases but were most prominent in Case 1. While buildability issues are caused by the two problem types, it can be reviewed as separate aspect of designs. Buildability issues were especially observed in cases 1 and 2.

INSUFFICIENT SPACE RESERVATIONS

Insufficient space reservations can be caused by two mechanisms: built spaces are smaller compared to designs or used equipment are larger compared to designs. These problems can lead to equipment not fitting in their designated places or significantly hindering the maintenance of equipment. Insufficient space reservations were mostly observed in Case 3. Existing structures and accuracy of architectural and structural models are key differences in renovation projects compared to new constructions. In Case 3 most of the documented space reservation issues were related to faulty or non-existent measurements of existing structures.

Due to the lack of measurements, heating, ventilation, and air conditioning (HVAC) designer had to use architectural drawings as a starting point and was forced to rely on their accuracy.

In Case 3 there were many situations where corridor was narrower than assumed in designs and installers had to improvise. Figure 1 shows an example of this, where narrow corridor meant that all the ducts could not fit in the corridor and installer had re-routed one duct to be visible in classrooms which do not have suspended ceilings.

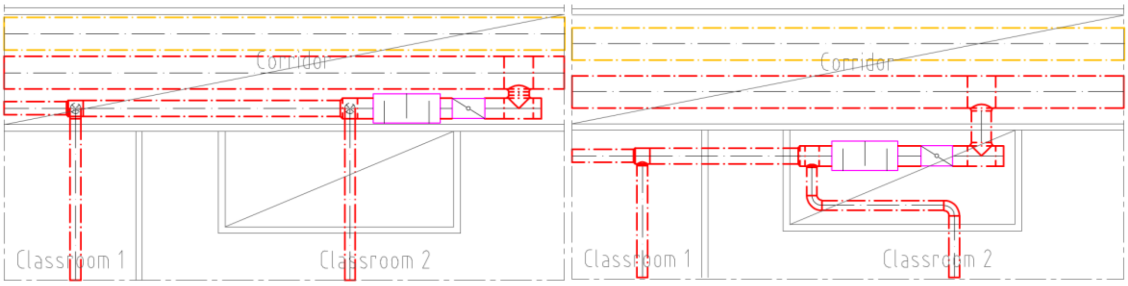

Figure 1: Left (1a) shows designers solution and right (1b) shows the installers solution. Installer had routed the supply air duct visibly in classrooms due to insufficient space in corridor suspended ceiling.

Another deviation was in technical room for ventilation where air handling units (AHU) had been arranged differently to designs, shown in Figure 2. The reason was smaller room compared to designs and as the result one AHU did not fit into its designed location. The installed solution is problematic for maintenance as AHU: s should have free space in front, equalling their depth, for replacing filters and other parts.

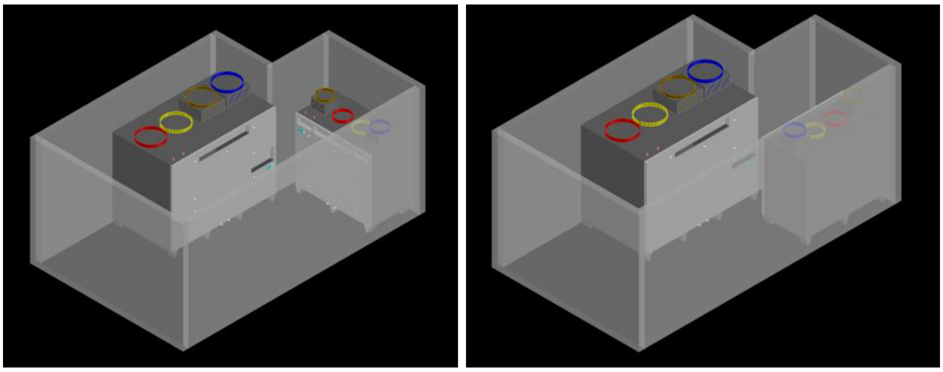

Figure 2: Designed arrangement of air handling units on the left (2a) and installed arrangement on the right (2b).

MISSING MODEL COMPONENTS

BIM coordination is not able to solve issues which cannot be seen in the model. There are many things that affect installation but are not necessarily included in the BIM. These missing model components often include, for example, hangers for MEP systems, small structural elements, and electrical cables. All these objects occupy space and can cause unforeseen problems in installation if not modelled.

In Case 2 there were several examples of walls being modelled to the elevation of suspended ceiling while they should have been modelled and were built to slab height. This leads to penetrations in suspended ceiling space which cannot be seen from the model. According to installers this caused some changes in pipe routing to avoid penetrations of concrete or brick walls. Figure 3 shows an example of re-routing pipes and its effects on the number of penetrations in a toilet group. Blue, red, and magenta lines represent the routes of domestic cold, hot, and circulation pipes. Red dots mark voids that need to be drilled on site. Figure 3a is the design solution for both pipes and walls. Figure 3b illustrates how the walls were built and how the solution affected the number of voids. Figure 3c shows the installers solution with real wall heights. The numbers of voids in the three solutions were 11 for 3a, 23 for 3b, and 18 for 3c. The difference between 3a and 3b shows the number of voids that the designer did not see from the model due to walls not being modelled high enough. The installer was able to eliminate 5 voids compared to the designer's solution.

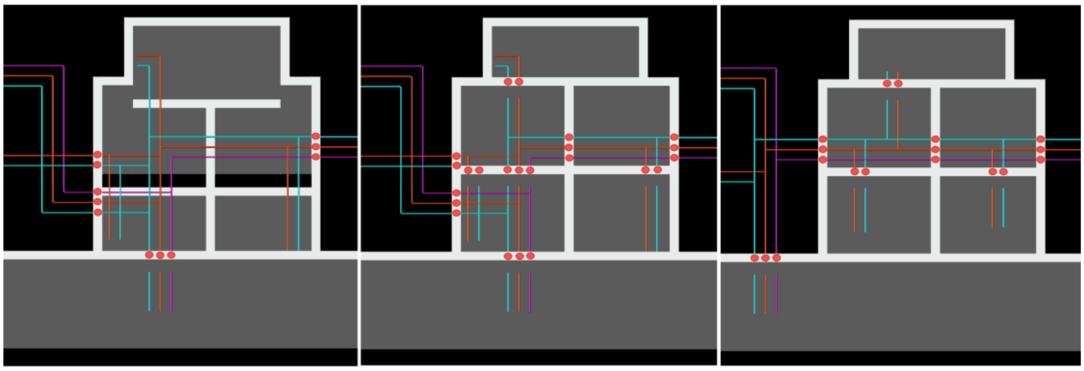

Figure 3: Pipes penetrating wall marked by red dots in three different cases. 3a, situation in BIM model. 3b, designed solution in reality. 3c, installers solution. The cases respectively have 11, 23 and 18 penetrations.

Supporting structures for interior walls and suspended ceilings can similarly cause collisions on site as these structures are not modelled. Figures 4a and 4b show how a supporting structure for suspended ceiling caused the need to lower the ceiling height. Figure 4a shows the design solution where ventilation duct penetrates the vertical surface of suspended ceiling and Figure 4b shows the supporting structure of suspended ceiling as it was built. The designed duct did not fit between the horizontal structures and the ceiling height had to be changed.

Third example of deviation caused by supporting structure can be seen in Figures 5a and 5b. The design model is missing a structure for movable partition wall where the wall can be stacked. Figure 5a shows the designed situation and 5b shows the installers solution. As a result of this structure, the installer had moved the silencers of two ducts away from the wall and re-routed the yellow extract duct to avoid collision with the supporting structure. The larger duct was installed higher compared to design which made it impossible to install the smaller ducts above the larger one. Installed solution is more difficult to install as it requires going through the supporting structure and using more parts for re-routing ducts, and it may result in worse acoustic properties when silencers are not installed beside structures.

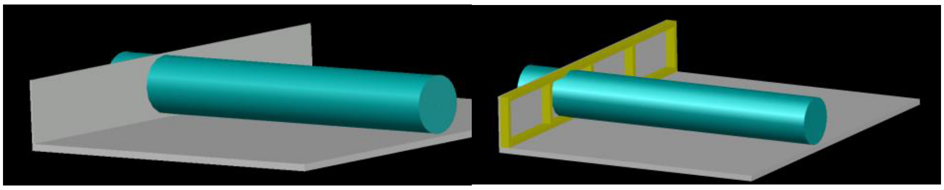

Figure 4: Duct penetrating the vertical wall of a suspended ceiling. 4a shows as-designed solution. 4b shows the supporting structures needed for installing the ceiling. In 4b the duct does not fit between the horizontal structures.

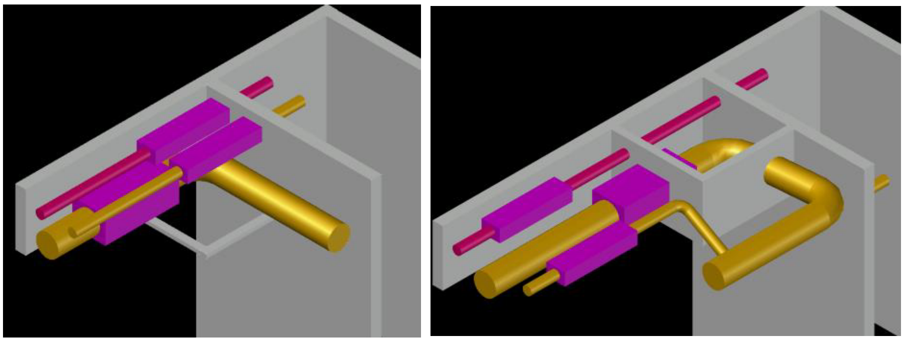

Figure 5: Ventilation ducts and structures as designed (5a, left) and as built (5b, right).

BUILDABILITY

Considering buildability is an important part of BIM coordination and neglecting it can result in clash free models that are impossible to construct. Of all the studied cases, the highest level of coordination was in Case 2 and the lowest in Case 3. In these cases, coordination was focused on eliminating clashes which is reflected in the following examples. Buildability is highly connected to missing model components and insufficient space reservations but it can be considered as individual dimension as well. In this case buildability means for example that there is enough space to make the installations, there is space to use scaffolding for ceiling installations, there is room for using tools, or the order of installation is reflected in designing.

In apartment buildings with decentralized ventilation, bathrooms are typically used for placing the AHU and the suspended ceiling of bathrooms have many ducts in a small space. This can result in difficulties considering buildability. In Case 1 the ventilation installers had made changes to one bathroom type to make more space for installation by re-routing one duct, as seen in Figure 6. The re-routing was possible without changes to other designs as the adjacent room had similar suspended ceiling to bathroom which enabled re-routing the duct. This solution gave more space to the bathroom as the number of ducts decreased and the silencer was installed to the adjacent space.

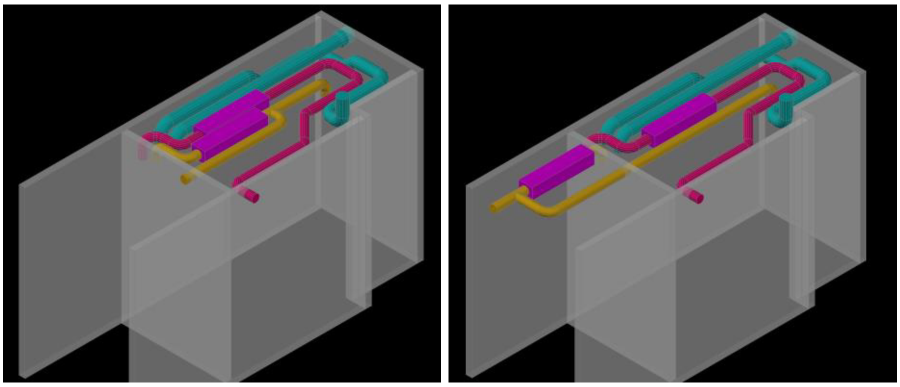

Figure 6: Ventilation ducts in suspended ceiling of bathroom and adjacent hall. Designers solution 6a on the left and installers solution 6b on the right.

Installation sequence should be reflected in designs as changing the sequence in construction phase will lead to clashes that could not be solved in designs. The coordinated models work only if they are followed. Schedule issues can affect the sequence of installations as had happened in Case 3 where plumbing works were changed to be made first. The reason was that the plumbing installations can be made during other dusty stages while ventilation installations require a dust free environment. This resulted in many deviations where pipes were installed above ducts even though ducts were designed to be installed as highest.

Duct crossing takes a significant amount of height and should be avoided or designed to fit into the installation space. In Case 1, there were duct crossings in suspended ceilings that could not fit the reserved space as designed. Figure 7 shows the crossing of two 125 mm ducts with insulation. Left side version is the designed solution and right side version is the installed version. Left hand version does not fit in the space above suspended ceiling. This is clearly shown in the BIM. However, the issue was not solved by either HVAC designer or architect. HVAC designer could have solved the issue by using the same part as the installer had used or a rectangular duct and the architect could have lowered the suspended ceiling or raised the story height. Installer had solved the issue by using a factory made crossing part that enables making the installation in the reserved space. Similar case in Case 3 is shown in Figure 8 where a crossing of two 400 mm diameter round ducts was designed to be done with rectangular duct in the size of 400mm x 200mm, as shown on the left side. Installers solution, where the crossing was made using round duct of 250 mm in diameter, can be seen on the right side. The reason for the change was given by the installer as 250 mm round duct requires the same height as 200 mm rectangular duct with flanges and using a round duct is significantly cheaper and easier to install. Using the round duct causes similar pressure loss compared to the rectangular solution so there is no impact to the functionality of the system.

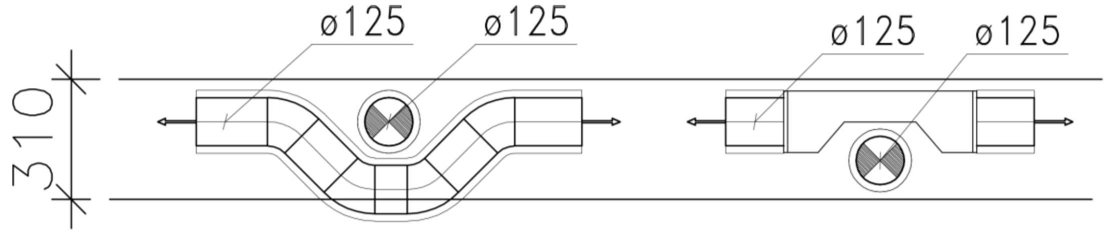

Figure 7: Using special crossing part to fit ducts into suspended ceiling without changing room height.

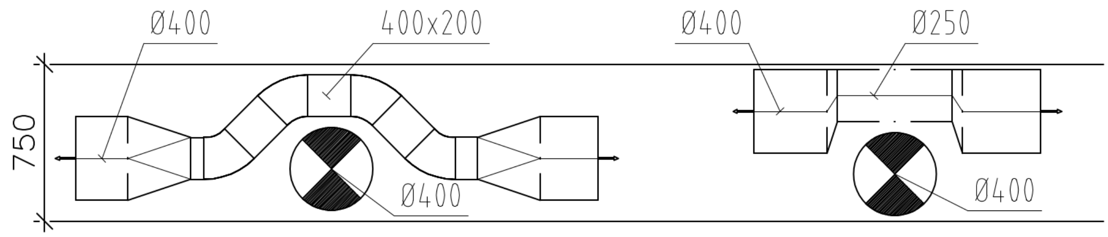

Figure 8: Changing rectangular crossing into round duct for a cheaper and faster installation.

Figure 9 shows a different case of installer changing parts for easier installation. The designer had used 90° elbow in turning a duct from vertical to horizontal under a concrete slab as seen on the left. The installer had changed the bend to a T-branch. This change enabled combining cleaning cover to the T-branch and continuing the horizontal duct in correct elevation and using fewer parts compared to designers solution.

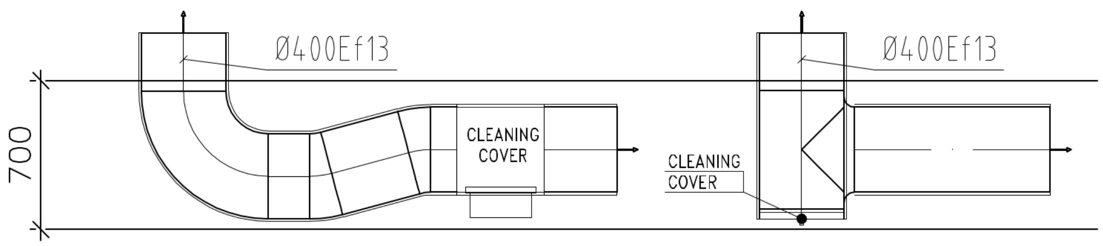

Figure 9: Changing of 90° bend into T-branch to minimize part and space usage.

INTERVIEW OF INSTALLERS

The reasons for deviating from designs are not always obvious and the feedback loop from installation to designing is minimal. For bridging this gap, installers were interviewed on site regarding specific deviations and in general about improving designs to better consider buildability. In addition to the issues described previously the installers identified areas for improvement, these are listed in Table 2.

Table 2: Suggested improvements for MEP designing from installers.

1	Assessment of buildability should be part of BIM coordination.
2	Scheduled order of installation should be reflected in designs.
3	Systems need to be considered on building level as opposed to story level.
4	Unnecessary on-site penetrations of concrete or brick walls should be avoided.
5	Architectural and structural models should be more accurate, especially in renovation projects, to consider existing structures.
6	Unmodelled components such as hangers should be further considered in designing.
7	When defining voids for concrete elements, space for insulation and hangers should be considered.

Many installers mentioned buildability in some form. Their experience was that BIM models always have clashes and buildability is not considered in designing. In addition to the examples given earlier in this paper installers mentioned considering room for using scaffolding. Toilets in Figure 3 were one location where working in the ceiling according to safety requirements using a scaffolding is difficult due to constrained space and the installers were forced to using ladders which is not permitted officially due to safety reasons. In this example they had also minimized the difficult tasks by re-routing pipes.

Scheduled order of installation should be reflected in designs. Systems that will be installed first should be designed as highest since installing will advance from top to bottom. To enable efficient installation constant elevations for systems make installation easier. Frequent changes in installation height means that installers cannot complete their own systems but instead need to wait other systems to be built to continue their own installation.

Especially in large buildings, design tasks can be divided by floors to reduce design time by adding designers. Sometimes this leads to suboptimal solutions which one installer had noticed on site. He suggested that designers should consider systems more on building level and to make sure that the systems are functioning and efficient as a whole.

Penetrations made on site are not desired as the MEP installers often have to drill them by themselves or wait for the main contractor to do it and this decreases the time they can spend making actual installations. These should be avoided if possible by routing pipes and ducts differently.

Existing structures caused many deviations in Case 2. Ventilation installer suggested that available spaces and load bearing structures should be measured in designing to solve problems better in design phase.

Many installers mentioned hangers as an area of development. Hangers were not modelled in any of the studied cases, and it is not customary in Finland. This means that space reservations for hangers are not considered and installers need to coordinate all the clashes caused by hangers. Changing locations of already installed hangers to accommodate other trades is common.

Voids in elements need to be placed so that the pipes or ducts can be installed into them. In some cases, the voids are too close to the ceiling and installing hangers above the parts becomes difficult. Ceilings can also have sound absorbing materials that are not modelled but affect the free space between voids and ceiling.

DISCUSSION AND CONCLUSIONS

The objective to convey designers' intent into installation via designs is not realized fully by using current design practices, even when BIM is used for coordination. In many cases it is not possible to execute the designs exactly as intended. In some cases, it could be said that the designs are used as schematics and routing between two points can be changed as long as the points are connected in correct sequence. The study also showed that improvisation leads to more improvisation and unclear designs lead to waste, as predicted.

Installers have a good understanding regarding buildability and in most cases had good reasons for deviating from designs. In some cases, their changes improved the engineer's solution and in some cases the changes resulted in decreased functionality. Based on the observations and interviews, having contractor comment on design and suggest changes could remove many of the documented deviations and increase productivity in installation phase. Contractors could contribute to solving possible issues in designs phase and optimizing designs based on their experience and typical construction practices. Knowing the building schedule and planned order of installation by early contractor involvement would enable designing for the installers needs.

BIM coordination does not guarantee collision free installation even if models are clash free, as was in Case 2. BIM coordination can only resolve clashes which are visible in the model. Many of the documented deviations were caused by unmodelled objects. These problems could be solved by increasing the LOD of all models. Potential of using BIM was not realized to fullest in any studied case, assessment of buildability was left undone in all cases. Increasing the LOD is a requirement for effective assessment of buildability as only visible issues can be resolved.

Observed deviations from case sites were divided into three categories: insufficient space reservations, missing model components, and buildability. All the problem types could have been solved before installation by more accurate designing. Based on our observations to improve productivity in installation we suggest the following changes to designing. 1. Designing must be done using BIM. 2. Shift from collision free models to buildable models. BIM coordination must be part of designing and it must include resolving clashes and assessment of buildability. 3. Increasing the LOD and accuracy of designs to better enable steps 1 and 2. 4. Contractor should be involved in designing and giving feedback especially on buildability, schedule, and order of installation. 5. Cost optimization based on components should be part of designing.

While positive effects of BIM use in designing have been documented extensively and coordination practices have improved continuously (Tommelein and Gholami, 2012; Jang and Lee, 2018; Khanzode et al., 2008), we found that these practices are not followed in projects in Finland, and likely other countries, where prefabrication of MEP is not yet commonplace. Therefore, we primarily suggest adopting already proven BIM practices in all types of projects. Secondly, we suggest a move from clash free models to buildable models. Projects using modelling and BIM coordination are focused on achieving clash free models but currently neglect assessing buildability in many cases. This is partly due to low level of detail in design models and designers' lack of installation knowledge. Increasing the level of detail in all design models will benefit BIM coordination as more issues can be resolved in designing. Modelling of hangers for example is common practice in markets that use prefabrication and having these additional details will help solving issues in design phase. More research is needed to determine a reasonable level of information need to guarantee that further modelling effort supports assessment of buildability.

We presented prefabrication designs as closest existing example of ideal designs. When studying barriers in adopting prefabrication in the Finnish market Lavikka et al (2021) found designers are lacking capabilities for detailed level design. Our results support this finding with many examples where buildability could have been better considered, while we recognize that contractual issues and tight deadlines may also be factors. Our proposition to solve this issue is involving contractor and installers in design phase and letting them affect designing by analyzing buildability based on their experience. One proven method for incorporating scheduling into designing is 4D BIM (Koo and Fischer, 2000; Buchmann-Slorup and Andersson, 2010), which is not widely used in the Finnish market. Using contractor knowledge in designing and having contractors designing detailed models is commonplace in markets where prefabrication is widely used (Khanzode et al., 2008). Having a feedback loop from construction to designing is critical for identifying and removing problems (Tommelein and Gholami, 2012). Contractors could also help on optimizing designs to decrease material costs. Our results showed that installers are already doing optimization on site to reduce work time and material cost.

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MANAGING USER REQUIREMENTS IN SOCIAL HOUSING UPGRADING

Samira Awwal[1], Patricia Tzortzopoulos[2], Mike Kagioglou[3], and Joao Soliman-Junior[4]

ABSTRACT

User requirement management is essential to improve value generation in construction projects. Requirements management is also vital in the context of social housing upgrading/retrofit projects, as such projects generally involve a poor consideration of user needs. Design science research is adopted to propose a process model to support the identification of user needs in the social housing upgrade context. Data was gathered through an empirical study carried out in an upgrading project in the UK. The model includes the use of BIM (Building Information Modelling) based tools. The model can help elicit users' needs and values through a participatory approach and the early inclusion of stakeholders in design decision-making. The process model contributes to an improved approach to managing user requirements, which will promote better value generation through retrofit projects.

KEYWORDS

User requirements, social housing upgrading, process model, building information modelling.

INTRODUCTION

Social housing upgrading provides an opportunity to solve housing deficits (Jensen et al., 2018). However, such upgrading/retrofit projects are challenging to manage (Carvalho et al., 2019). These challenges often result in overlooking user needs and consequent poor value generation (Blomsterberg & Pedersen, 2015). User value can be generated through the appropriate identification, processing and communication of requirements to assist design decision-making (Parsanezhad et al., 2016; Koskela, 2000).

Requirements management is essential in Lean. It includes capturing and eliciting client requirements, as well as monitoring the value generated from the user's point of view (Koskela, 2000). The approach involves gathering and processing information, and implementing strategies to support value generation throughout the design and construction phase (Jallow et al., 2014).

In the social housing context, there is a push towards upgrading/retrofitting the existing housing stock to achieve better energy efficiency. Such upgrading projects also can be an opportunity to increase user satisfaction (Kowaltowski & Granja, 2011; Baldauf et al., 2020).

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The conflicting interest among stakeholders and end-users highlight the need for a robust method to capture user needs during such projects (Koskela, 2000).

POEs (post-occupancy evaluations), surveys and interviews are often used to elicit user requirements (Miron &Formoso, 2003). BIM can also be used for storing and structuring requirements, and connecting that information to building models for visualising requirements (Parsanezhad et al., 2016; Baldauf et al., 2021). This paper proposes a process model (adapted from Baldauf et al., 2020's paper) to illustrate user requirements management with BIM in the specific social housing upgrading process.

REQUIREMENTS MANAGEMENT

User requirements are often referred to as objectives, needs and expectations of the client/user in a construction project (Jallow et al., 2014; Kamara & Anumba, 2000; Kamara et al., 2002). The requirements management process incorporates initiation, development, adaptation and communication or requirement throughout the project (Barrett et al., 1999; Kamara et al., 2002).

Baldauf et al., (2020) proposed a client requirements management model with the use of BIM tools, which includes the following steps (i) identify-understanding the context and capturing requirements; (ii) analyse-interpretation of requirements; (iii) structure - organising the requirements); (iv) translate - conversion of requirements into product specification; (v) store ; (vi) prioritise - identifying the critical requirements from the categories from the users and stakeholders; (vii) communicate - liaise among stakeholders to facilitate design decisions to avoid conflict; (viii) assess - assessing the product development; to check if all the requirements are met (Baldauf et al., 2020, 2021; Bryde et al., 2013; Jallow et al., 2014; Kamara et al., 2002; Luo et al., 2010; Miron & Formoso, 2003; Pegoraro & Paula, 2017).

USE OF BIM IN REQUIREMENTS MANAGEMENT

BIM can facilitate collaboration between stakeholders by providing easy access to information (Jallow et al., 2014; Kamara et al., 2002; Baldauf et al., 2021). Past studies have developed computer tools allowing connections between requirements and product models (Baldauf et al., 2020; Luo et al., 2010). Figure 1 illustrates connections between client requirement management (CRM) steps and BIM.

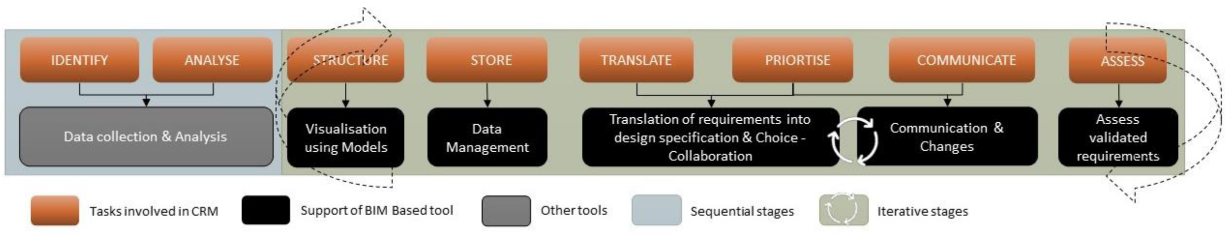

Figure 1: Connection between CRM steps and BIM

Potential BIM benefits in client requirement management are described below for further understanding:

- Data Management - BIM serves as data storage in a single centralised database system and facilitates easy and accessible information to the stakeholders through the 3D model. (Meadati & Irizarry, 2010). BIM allows the storage of requirement information so that the stakeholders' requirements can be accessed and reused at particular points of the project (Baldauf et al., 2021; Jallow et al., 2014; Luo et al., 2010). BIM stores lifecycle data requirements, and operational information that can be used in the requirements management (Jallow et al., 2014; Nørkjaer Gade et al., 2019).
- Visualisation-Visualisation is one of the primary characteristics of BIM and there are potential benefits when implementing 3D/4D BIM in the construction industry to

structure user requirements (Baldauf et al., 2020, 2021; Wang et al., 2014). BIM allows improved client service, using an accurate visualisation (Azhar et al., 2011).

- Collaboration - BIM allows collaboration through a faster and more effective process (Baldauf et al., 2020). All the stakeholders' requirements should be incorporated at the initial stage (e.g., the Briefing stage (Jallow et al., 2014). There should be a connection between the requirements and objects in product development, that will allow value generation in the process (Kiviniemi, 2005).
- Communication & changes- BIM allows changes in product attributes. It contributes to the communication in real-time changes in requirements that can be refined in the model recurrently (Awwal et al., 2022; Luo et al., 2010). BIM provides quicker simulations to simplify the generation of alternative design solutions (Azhar et al., 2011).
- Assess - BIM administers sufficient support for assessing design decisions, depending on validated requirements (Tzortzopoulos et al., 2019; Soliman-Junior, Awwal, Tzortzopoulos, et al., 2022). It can be used to check if the design process of the product considered stakeholders' requirements to ensure value generation (Baldauf et al., 2020).

Requirements management plays a vital role in generating value for users. It is well known that BIM can support the modelling of client requirements (Baldauf et al., 2020). However, there is little evidence in the literature of adaptations needed for its use in the context of social housing upgrades.

RESEARCH METHOD

RESEARCH DESIGN

Design Science Research (DSR) was adopted in this investigation. The products of Design Science Research are (i) constructs; (ii) models; (iii) methods; and (iv)implementations (March & Smith, 1995). This investigation proposes a process model to manage client requirements in the social housing upgrading context (see Figure 2).

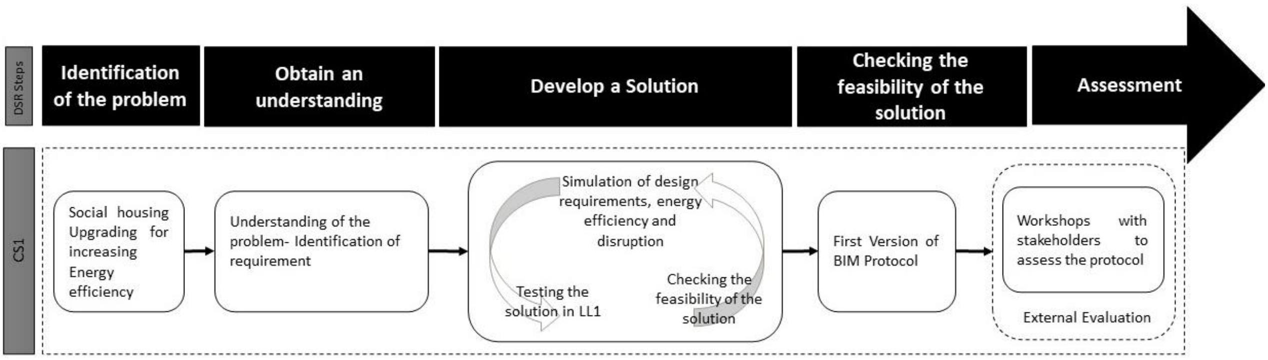

Figure 2: The Research Design

Each research phase consists of five steps based on (Kasanen et al., 1993)'s model : (i) identification of the problem; (ii) obtain an understanding; (iii) develop a solution; (iv) check the feasibility of the solution and (v) assessment.

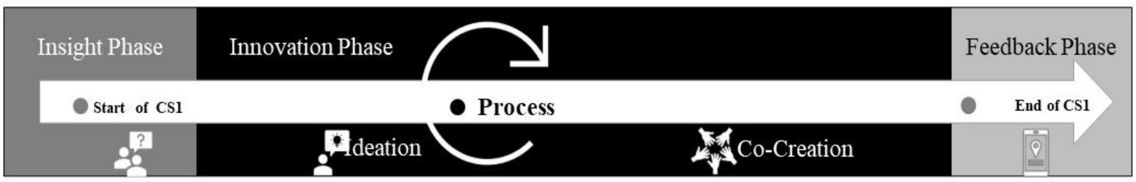

Figure 3: The Phases of the Case Study

The data was collected through the retrofit of 8 social housing dwellings in West Yorkshire, UK. Three workshops were developed to identify user needs and help reduce conflicts between stakeholders, supporting a participatory upgrading process (Keyson and Lockton, 2016). The workshops included: a. Insight; identification and capture of user's requirements; b. Innovation; consisting of ideation and co-creation; and c. Feedback; evaluation (see Figure 3), that follows an iterative process to foster collaboration (Tang & Hämäläinen, 2014).

The workshops were planned to involve the local council, architects, retrofit coordinator, construction company, and tenants/users of the social houses to be upgraded). However, only users and the local council were effectively engaged in the workshops. The council selected 8 houses for retrofit (See Figure 4), mainly aimed at improving their energy efficiency.

Figure 4: Before (left) and After(right) image of the social housing retrofit case study

The retrofit work is now completed (See Figure 4), and the following components were changed/implemented; (i) heat pumps were installed, gas boilers and cookers were removed ending reliance on fossil fuel; (ii) triple glazed windows, loft insulation, cavity wall insulation and external wall insulation were provided, (iii) new roofs were fitted and chimneys closed to remove a possible cold bridge; (iv) Photovoltaic panels and solar thermal panels were installed to create renewable solar energy (v) new entrance doors installed, new bins stall and backyard fences are installed. Figure 5 depicts the timeline of the case studied.

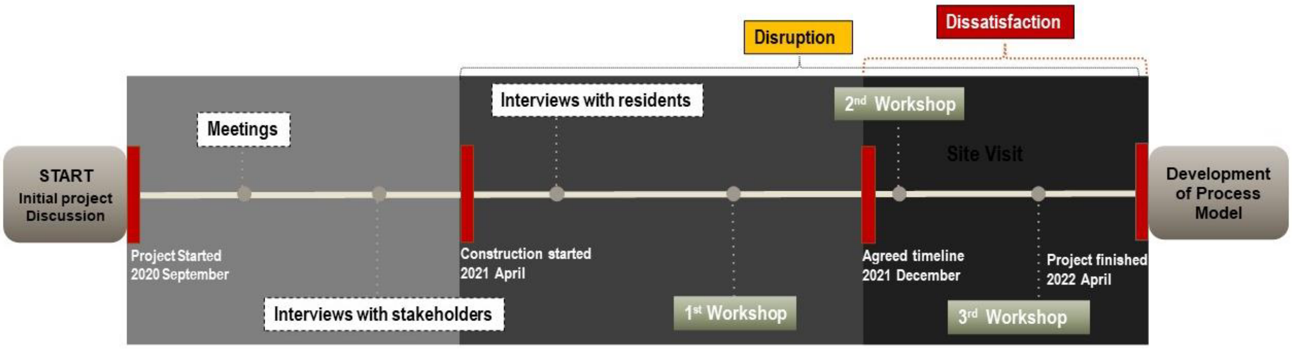

Figure 5: Timeline of the case study

The empirical data was collected from 11 interviews, which included 5 residents from the selected upgrading project and 6 residents from the wider estate. The interview protocol consisted of (i) residents' satisfaction with their homes; (ii) Laddering (what are the three most important things to be upgraded in the house and why); (iii) profile of the residents.

Workshops (see Table 1) were facilitated to capture requirements and to evaluate design versus users' needs. The 1st workshop included four members of the council and four researchers, targeting to better understand how different tools help capture user requirements and help increase end-user participation in the upgrading project. The 2nd and 3rd workshops included three end-users and four researchers, aiming to further understand requirements and experiment with the use of digital models.

Table 1: Sources of Evidence

Source of Evidence	Stakeholders	BIM-Based Tool	Occurrence
Workshop 1 Testing tools to understand requirements and values	• Four Council Members Four Researchers	• BIM: Exiting model, value cards& evaluation of tools	Developed- 11 Jan 2022
Workshops 2 & 3 (i) Testing requirements through BIM immersive experience (ii)Design vs Values	• Four End Users (Tenant) Four Researchers	• BIM: Existing Model & developed design model, value cards and evaluation tools	Developed- 21 Feb 2022

RESULTS

Table 2 presents some interview results, including the highest dissatisfaction elements identified in the existing houses. These indicate focal elements for consideration as part of the upgrade of the houses. Unfortunately, not all requirements were considered in the upgrading process by the council due to financial constraints.

Table 2: Dissatisfaction with product attribute

Key Criteria	Product Attributes	Dissatisfaction Rate
• Dimension and space layouts	• Dining space, Kitchen, Storage	High
• Materials, finishes, equipment	• Doors, windows, wall cladding	Very High
• Acoustics, temperature, privacy	• Winter temperature, privacy, noise	Very High
• Env.quality, safety, accessibility	• Accessibility for the elderly	High
• Consumption, maintenance	• Energy costs/ utility costs, heating system performance	Very High

During the workshops, BIM models were used for (i) Real-time rendering linked to BIM; (ii) BIM models used in a 3-sided Immersive Cave. BIM models of the houses as existing, and the newly designed solution were developed and displayed in the workshops (see Figure 6). Examples of alternative solutions (e.g., colours of windows, fencing materials etc, scaffolding construction) were explored. The tools developed assisted in eliciting user requirements. The tools can, in the future, be used to support generating design options and evaluation through visualisation.

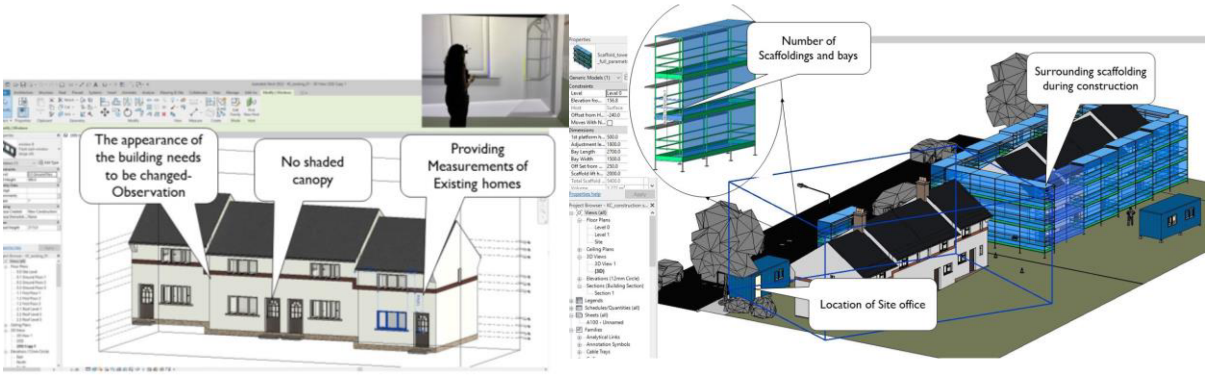

Figure 6: The BIM Model developed in the CS1

The BIM tools foster communication and collaboration by considering multiple stakeholders' needs, aiming to reduce conflicts and misinterpretations, and supporting improved value generation.

THE PROCESS MODEL

The proposed model adopts the stages presented in Baldauf et al. (2021) requirement management model, including the steps displayed in Figure 1. The process consists of sequential and iterative stages. Figure 6 shows the process model to manage user requirements with BIM in social housing upgrading projects.

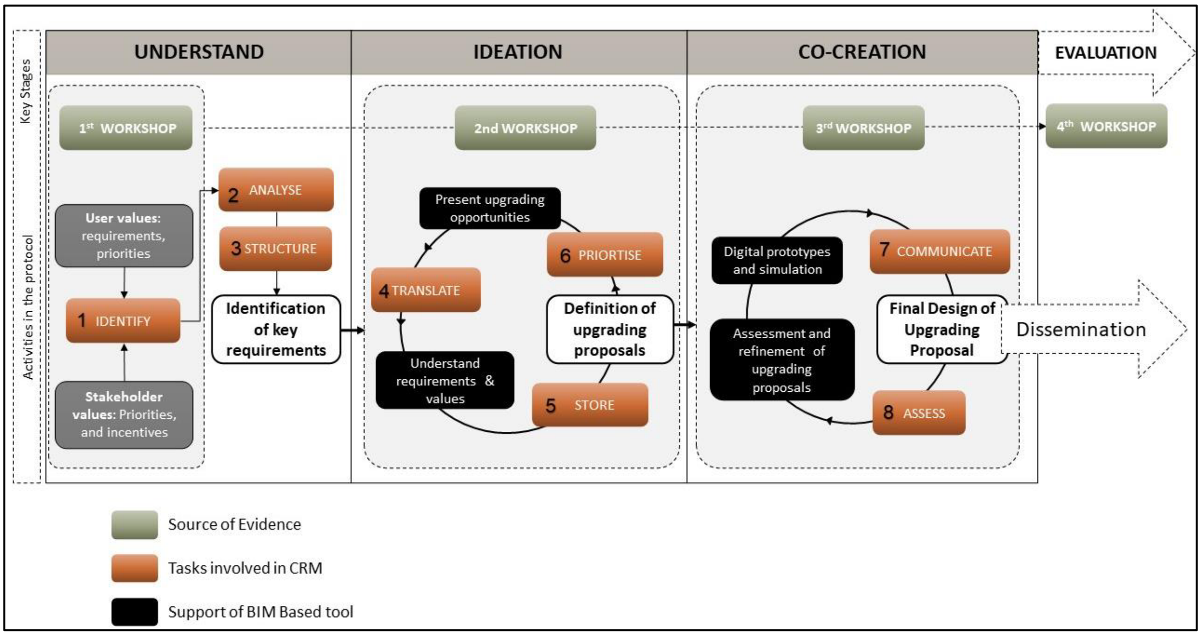

Figure 7: User's requirements management process model for social housing retrofits

The process starts with the identification of stakeholders and their priorities, which need to be analysed and structured in the next phase. The structured requirements need to be embedded in design solutions, and connected in BIM to architectural elements such as building spaces, the colour of the fence etc. BIM (e.g., Autodesk Revit) enables the required data to be stored and reused.

Design alternatives for the upgrade project should be presented visually (through diverse BIM models, i.e., one per alternative to be discussed) and shown to stakeholders. Such joint discussions should enable any conflicting requirements to be identified, and joint decision-making to happen. All information should be accessible to multiple stakeholders at various stages of the design process.

BIM-enabled experimentation through immersive environments, digital prototyping and animation/video rendering allows end-users to directly participate in the design process, which will support the generation of user value in the upgrading process. The last phase involves an evaluation of the process. The main steps are further detailed as follows.

Step 1-Identify: commences with the identification of stakeholders and capturing requirements. These priorities will be based on the purpose of the upgrading project (e.g., energy efficiency upgrading). In the case studied, the initial requirements were limited to energy efficiency, without further consideration of other users' requirements. Hence, mostly product attributes were considered (e.g., energy efficiency, installation of heat pumps), rather than connecting the project users' needs.

Step 2-Analyse: In the analysis phase, multiple sources of information should be considered for capturing and eliciting requirements. For instance, in this investigation, different stakeholders, such as councillors, retrofit co-ordinator, council members, design and construction team and tenants were interviewed. As there are boundaries regarding cost and construction issues, not all initial requirements may be implemented in the upgrade. It is important that these are prioritised accordingly, with input from all stakeholders.

Step 3-Structure: This is based on organising the collected requirements. This can also be based on existing taxonomies (e.g., Baldauf 2020's structure). Structuring the requirements will support the translation of the requirements into design solutions.

Step 4-Translate: Step 4 focuses on translating the requirements into design solutions. For instance, the initial requirements can now be connected to a digital model and presented to the stakeholders.

Step 5-Store: Requirements must be stored in BIM software and can be available to the main stakeholders. For instance, the information stored in the digital model in this investigation has been reused for eliciting client requirements in multiple workshops and meetings.

Step 6-Prioritise: BIM - can support prioritisation through the digital model. These are communicated to the stakeholders through virtual reality and real-time rendering. There are multiple stakeholders in social housing upgrading (e.g., tenants, council members, design, and construction team, retrofit coordinator etc) and their needs need to be considered.

Step 7-Communicate: Communication improves through the use of BIM. During the workshops, users pointed out that the digital models and real-time rendering enabled a much better understanding of the user of changes to be implemented in their homes and enable space for discussions on what would be most appropriate to be implemented, from the users' perspective. As discussed in (Soliman-Junior, Awwal, Tzortzopoulos, et al., 2022), the interviews also reported that BIM-based requirement models would support an improved understanding of the project.

Step 8-Assess: the requirements management process needs to be assessed at the end of the upgrade, so improvements can be implemented in next projects.

The above process aims to provide a better approach to facilitate the design of social housing upgrading projects and enable collaboration to manage requirements.

CLOSING REMARKS

Requirement management explores solutions for managing stakeholders' requirements in construction projects (Jallow et al., 2014). This research highlights the importance of requirement management in social housing upgrading. The discussion highlights that the adoption of the proposed process model can improve the generation of value and the ability of social housing users to co-create design solutions for the upgrade of their homes. End users and stakeholders (council, construction companies, architectural enterprise) are fundamental actors and their requirements should be key drivers in the design and delivery of upgrading solutions (Soliman-Junior et al., 2021).

The process model allows communication through visual management, iteration, and opportunities for feedback in the phases. A summary of how the process model addresses lean principles is presented in Table 3. The findings presented in Table 3 are consistent with some early synergies identified between Living Labs and Lean in (Soliman-Junior et al., 2021)'s paper.

Table 3: Lean principles and CRM Process Model in Social housing upgrading

Lean Principle (Koskela, 1993)	Process Model
Increase Value	• Requirement management focuses on early stakeholder collaboration, that generates value. • Participatory approaches are practised through ideation and co-creation. • The process model aims to support collective decision-making.
Increase process transparency	• Use of BIM to increase transparency and collaboration among stakeholders.
Use visual management	• Using BIM potentially allows for a real-time change in the models, and can be part of visual management processes.
Continuous improvement	• The process is iterative and allows for assessment and refinements in the design process.
Reduce cycle times	• The process allows accelerated feedback loops, minimising errors and thus contributing to the reduction of cycle times.

There are some limitations to this investigation. The artefact suggested (requirements management process model) was developed based on a single and relatively small empirical study. It should also be highlighted that only the researchers developed the BIM models and applied them in the case study to capture and elicit user requirements. This method is not thoroughly applied and tested in another case study; further research is needed to assess the applicability of the artefact. The scope of product attributes to be upgraded was limited due to cost and the council's suggestions. Further empirical data is needed to generalise the artefact's applicability to other upgrading projects.

Despite the limitations, the contribution of this investigation is the introduction of the steps such as identifying and capturing the requirements of end-users, structuring the digital model, storing information, and accessing them at different stages of the project to avoid conflict, and the use of the BIM-based tools in the process to increase collaboration among stakeholders. Also, lean construction practices as described in Table 3 could be further enhanced by using the process model in social housing upgrading. These provide the opportunity to improve understanding of requirements at multiple stages (e.g., preliminary design, development, and construction phase) of the upgrading process, enabling problems to be addressed transparently and facilitating better communication among multiple stakeholders.

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MANAGING HUMAN-CENTERED INNOVATION WITHIN TVD IN HEALTHCARE PROJECTS

Patricia A Tillmann[1] and Stuart Eckblad[2]

ABSTRACT

Responsible for delivering major healthcare projects, the University of California in San Francisco (UCSF) has devised creative ways of reducing waste and increasing value through project delivery. In a previous paper, we described UCSF Health's journey to rethink project delivery practices. The adoption of Target Value Delivery (TVD) is a core enabler of their success. The University has consistently adopted TVD to deliver complex healthcare projects within or below their allowable costs. Previous papers have provided evidence and insights into why and how such success has been achieved. However, the focus so far has been on collaboration and cost management. This paper describes the strategies utilized to focus on and manage value generation. The term human-centered innovation was chosen to emphasize stakeholder engagement and empathy building as input to idea generation. This approach shaped how TVD is implemented in these case studies. Its analysis provided insights into complementary design and decision-making strategies traditionally used in TVD. In particular, the design strategies observed in this research expand the documentation of TVD best practices to include not only solution development strategies but also participatory and empathic ways of understanding, framing, and reframing design problems.

KEYWORDS

Target Value Design, Value Management, Value Generation, Integrated Project Delivery, and Healthcare Design.

INTRODUCTION

Target Value Design (TVD) is a lean design and construction method that focuses on achieving the target cost of a project while ensuring its quality, performance, and expected outcomes. In TVD, the cost is considered an input throughout the design process. Project teams steer the design process through trade-off decisions to achieve the target cost while maintaining the desired quality and expected performance.

Initially introduced in the manufacturing industry, the first time TVD was successfully adopted in the construction industry was in 2002, in the St. Olaf's College Project in Northfield, Minnesota, by the Boldt Company (Ballard; Reiser, 2004). Since then, the approach has increased in popularity and adoption in the U.S., generating lessons learned and best practices based on its practical application (e.g., Ballard, 2008; 2011).

The name TVD can be traced back to Toyota's Target costing approach. Target costing has been defined as a *"system of profit planning and cost management that is price-led, customer-focused, design-centered, and cross-functional"* (Ansari *et al*., 1997). Macomber et al. (2007) proposed a shift from "target cost" to "target value design" to emphasize that

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construction projects are not limited to cost and that the delivery of value to customers is paramount.

However, since its successful adoption in the early 2000s, its increased popularity has been associated with its ability to steer projects to meet or exceed financial performance successfully. Thus, its documentation in the literature focuses primarily on describing how those financial goals have been achieved in the different projects. At the same time, the aspects of managing value to customers are less explicit in the literature. Hence, the research question that motivated this study was: How can we improve value management within target value design to focus more on customer value (along with steering a project to a target cost)?

This paper aims to contribute to closing this gap by offering a perspective on managing human-centered innovation to focus on customer value. Such an approach has been successfully adopted within the application of TVD in multiple case studies. The term "human-centered innovation" was chosen to illustrate its focus on stakeholder engagement and participation in the TVD process. Human-centered design is a term often used to describe design philosophies and practices that offer a humanistic perspective on innovation theory and practice (Auernhamme & Roth, 2021).

The research method used in this paper is a multi-case study approach. Figure 1 summarizes the characteristics of all case studies. These case studies were selected because they successfully adopted TVD to deliver projects within their targets for costs, scope and performance, while adopting a unique approach to managing customer value. Data from the case studies started to be collected in 2013 through a research project. Data-gathering techniques changed over the years. From 2013-2016 data were collected by several researchers and graduate students from the UC Berkeley P2SL laboratory through interviews and document analysis. From 2016-2019 one of the researchers joined UCSF's Real Estate Department, changing data collection methods to focus group discussions, document analysis, and participant observation. In 2021, the same person joined one of the analyzed projects under UCSF Health, shifting data collection techniques to participant observation and interviews. This paper reflects on the data collected and insights gained over the years.

Table 1: Summary of Case Studies Characteristics

	Case 1	Case 2	Case 3	Case 4
	2005	2015	2015	2019
Contract Model[3]	**Modified CMAR**	**Modified DB**	**Modified CMAR**	**IFOA**
Initial Estimate	1.5 bi	275 mi	170 mi	4.5 bi
TVD Savings	200 mi	19 mi	TBD	TBD

A LOOK THROUGH THE LENSES OF HUMAN-CENTRISM

Human-centered design (HCD) is a term often used to describe design philosophies and practices that offer a humanistic perspective on innovation theory and practice (Auernhamme & Roth, 2021). This approach generally implies an active engagement of customers in the product development process (Dell'Era & Landoni, 2014). The concept of HCD is rooted in the belief that the design process should be centered on empathetic thinking and focused on the needs, perspectives, and experiences of the people who will use the design solution.

The empathic design was presented as a process that involved observation, data collection and analysis, and iterative prototyping. Most significantly, it was identified as a way to uncover people's unspoken latent needs and then address them through design (Leonard & Rayport, 1997). It relies heavily on ethnographic research methods to uncover not what people are doing

[3] CMAR – Construction Manager at Risk, DB – Design Build, IFOA – Integrated Form of Agreement

but also the reason behind their actions in an attempt to understand how people make sense of what they do (Diller, Steve; Shedroff, Nathan; Rhea, Darrell, 2005).

Beckman and Barry (2007) explain that HCD belongs to a second generation of design theories and methods that depart from traditional design approaches. On the one hand, the first generation leveraged operations research and optimization techniques, leading designers to think explicitly about how to decompose a complex problem into a set of smaller, well-defined problems, assuming that all these problems can be predicted, well-defined, and made explicit upfront. On the other hand, the second generation focuses on collaboration, co-creation, and leveraging the tacit knowledge of stakeholders, who are deeply engaged in the design process. The design then shifts from a clear-cut problem-solving process to a problem-formulating process in which getting to a collectively acceptable starting point (so that appropriate resources could be committed to solving the problem) is the core of the effort (Beckman & Barry, 2007).

There are several key differences between first and second-generation design theories and methods. Firstly, the designer takes on a facilitative role, guiding and supporting the stakeholders in the design process. Secondly, stakeholders' involvement changes from consultation to active participation in the design process. Thirdly, the design is iterative and flexible, allowing for multiple rounds of feedback and iteration, generally resulting in a solution shaped by the stakeholders' collective perspectives and experiences.

Based on human-centered design literature, Beckman (2022) developed an "innovation cycle," suggesting that human-centered innovation occurs in four quadrants within a learning cycle. This "innovation cycle" was used in this paper to guide empirical data collection and support the understanding of findings. Its four elements are described as follows (Quadrants 1 and 2 represent the "understanding the problem" or "why" portion of idea generation, whereas Quadrants 3 and 4 represent the "solution finding" or "how" portion of idea testing and implementation):

- Reflective observation and empathy building (Observe and notice - Quadrant 1): Fostering empathy for customers by considering their experiences and needs throughout the design process. Ethnographic research methods can help designers understand the emotional, social, and physical aspects of customer experiences.
- Abstract conceptualization (Frame and reframe - Quadrant 2): It is the understanding and synthesis of data gathered. It is the process of integrating different components to create new experiences. Frame and reframe is the process of getting to abstract conceptualization.
- Active experimentation (Imagine and design - Quadrant 3): Generating options and validating ideas through quick experiments. Iterating on the design solution based on feedback from stakeholders to ensure that the design meets their needs and requirements.
- Concrete experience (Make and experiment - Quadrant 4): Getting to the how. Materializing the ideas into artifacts or products. Testing it in the context of use.

Design theory and design methods are not topics covered in papers that describe best practices for TVD (i.e., Ballard 2008; 2011). By bringing this distinction between the first and second generations of design methods, the intent of this brief literature review was to highlight that different design approaches can support the adoption of TVD.

Past research has identified difficulties in applying tools associated with first-generation design methods, i.e., tools that aim to make all requirements explicit upfront (Sahadevan & Varghese, 2018) or to decompose problems into well-defined pieces (Lima et al., 2008). However, their theoretical underpinnings are rarely discussed. Similarly, several studies describe the successful adoption of methods and techniques that support dialogue and the collective understanding of problems-solution space, such as the collaboration that happens in multi-disciplinary design clusters, participatory design processes, set-based design, and Choosing-by-Advantages (CBA) (Ballard, 2011; Bascoul et al., 2018; Parrish & Tommelein, 2009; Arroyo, 2014). Although these approaches align with second-generation design theories, their theoretical underpinnings are rarely discussed. This literature review aimed to bring these distinctions to light so that these approaches and their contributions can be better understood from a theoretical standpoint.

EMPIRICAL FINDINGS

The University of California San Francisco (UCSF) is a public institution dedicated exclusively to health science. It focuses on research, education, and patient care, employing 3,400 faculty and 22,800 staff. UCSF generates nearly 43,000 jobs and has an $8.9 billion economic impact in the Bay Area, California, U.S.

UCSF Health is a department of UCSF focused on the delivery of care. It administers the University's hospitals and clinics: (a) UCSF Medical Center at Parnassus, Mount Zion, and Mission Bay; (b) UCSF Benioff Children's Hospitals in San Francisco and Oakland; and (c) Primary care and specialty clinics throughout Northern California. In addition, the department receives comprehensive project management services from UCSF Real Estate's Health Design & Construction unit, including programming and design, budget development, construction administration, inspection, and move-in assistance.

Since 2006, UCSF Real Estate's Health Design & Construction unit has undertaken a long journey to reshape project delivery practices within the University, introducing mechanisms to design, build and operate cutting-edge care facilities successfully. The University has chosen a very participatory route to deliver projects, which will be described in the following sessions.

1. The owner organization and key stakeholders

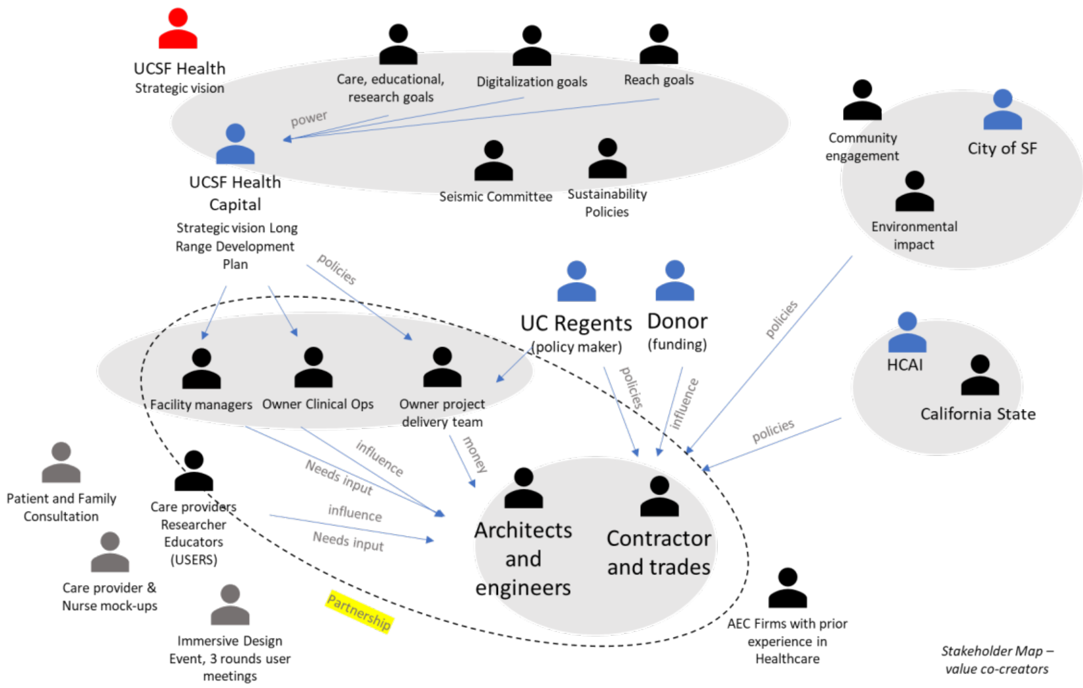

Figure 1: Key stakeholders involved (typical of all case studies)

There is a complex chain of stakeholders that influences the outcomes of a project. In these case studies, we have identified the following owner groups: (a) owner stakeholders who influence through their strategic vision for the organization and goals for the project, (b) owner clinical operations team, user groups, and patient representative groups that have more immediate requirements based on their current practice, (c) owner policy deployment teams, such as sustainability, seismic requirements, health policies compliance, etc. (d) owner technology department; and (e) facilities management group. Outside the owner organization, several key stakeholders also influence the project: (a) the city's community engagement program, (b) the city's environmental requirements committee, (c) the healthcare seismic state agency, and (d) the city's code compliance agency. The type of influence each stakeholder brings is also identified in the picture. The types of influences were characterized by: (a) policymakers, (b) resource control, (c) decision-making power, and (d) required input due to the participatory nature of project delivery.

For each of these stakeholder groups presented in the picture, there are accompanying documents that aim to clarify their requirements and set the parameters for the project. The first type of document applies to several projects within that organization, and examples are seismic and sustainability policies, city codes, university guidelines for new construction, etc. The second type applies to this project and developed in the front end of project development (before the project team was onboard) – business case and programmatic requirements. Finally, the third type is developed by the project team to capture the input of key stakeholders – project charter and conditions of satisfaction, patient and user surveys, user feedback on prototypes, community engagement feedback, etc.

Despite the efforts to make all requirements explicit and documented, this environment is quite dynamic - non-identified stakeholders emerge, new individuals replace existing roles, circumstances surrounding the owner and their business change, and with that, multiple requirements emerge continuously through project delivery. That creates tension between explicit and tacit knowledge with a never-ending need to review and update what has been documented.

To deal with this dynamicity and tackle the tacit knowledge around stakeholder requirements, an integrated project delivery strategy has been adopted to support a participatory process. As portrayed in the picture, a partnership is formed between representatives from the owner organization, builders, and designers. Important to note that in this case, the owner organization is represented not only by the design and construction management team but also by the clinical operations, the information technology, and the facilities management department within the University. In the project directories, about 20% of the individuals are from the owner organization.

2. The project delivery strategy

In previous papers, the authors explained the strategies used in these projects to increase collaboration and integration in project delivery (Melo et al., 2015; Tillmann et al., 2022). Regardless of contract type, all projects benefited from mechanisms to increase relatedness among participants, mitigate diverging interests and align participants with acting as one single team. In this paper, these mechanisms are summarized into three categories (Figure 2):

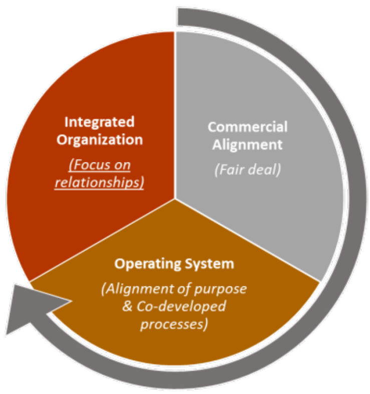

Figure 2: The three critical dimensions of collaborative project delivery

- Integrated organization (the ultimate goal): Co-location, multi-functional teams - the ultimate goal is to make companies behave like a single company with aligned objectives.
- Commercial alignment: sharing risks and rewards (when possible), being open about project finance, expected profit margin, and managing risks collectively.
- Operating system: Agreed upon routine and meeting cadence, Innovation in Design and Construction Center, Use of BIM for progress communication. Lean methods: Target Value Delivery and Last Planner System.

These mechanisms intend to focus on the relationship among parties and create a sense of unity in the purpose and processes of the project. This series of projects has been consistent with the successful application of Target Value Delivery, not only by meeting the target cost but also by meeting or exceeding programmatic and business case expectations.

The focus on value generation and value for customers was an expectation set since the early stages of all projects. In Case Study 1, for instance, the owner set the expectations for the team to *"make decisions by consensus but based on what is best for the project, not individual companies"* on Case 2, the selection process included the expectation that the team *"should work with the ultimate purpose to cure cancer"*; and on Case 4, the expectation set was that *"decisions are made based on what is best for patients."* During interviews, the owner explained that UCSF Health has a very easy-to-remember mission statement: Caring, Healing, Teaching, and Discovering. Those words are always mentioned when the team introduces themselves to potential partners during the selection process: *"This is who we are, and everything we do should always be to support this mission."*

One of the critical elements contributing to this focus on value is the project organizational structure and the owner-stakeholder integration. The projects are organized in Project Innovation Teams, multi-disciplinary cluster groups composed of designers, consultants, owner stakeholders, engineers, and builders. The owner stakeholders may also manage these clusters. In Case 4, for instance, out of the 12 PITs in the project, one is managed by the clinical, operational side of UCSF Health, acting as a liaison to UCSF clinical staff and users. Designers, builders, and consultants are also part of this PIT, gathering customer information, brainstorming design ideas, and developing options to validate with the different stakeholder groups.

In that same project, the other PITs were led by industry partners but also included the active participation of owner representatives, who helped co-design solutions and provided support to capture input from other stakeholder groups. For example, the MEP PIT was led by the general contractor but had the participation of owner representatives that engaged facilities management staff in providing information and feedback on design.

In Case 4, the decision-making structure also represented an integration of the owner's construction management team and the owner's clinical operations team, having seats on the Project Management Team and Senior Management Team and acting as liaisons to the University's leadership group.

An analysis of this team's weekly routine provided insight into how such a structure is operated. During a typical week, the team spent: (a) 50% of the time on Project Innovation meetings - generating ideas, discussing requirements, and resolving interdependencies or conflicts; (b) 25% of time consulting stakeholders and receiving feedback on ideas; (c) 12 % of time coordinating specialty work and solving interdependencies among systems; (d) 10% of the time on meetings to make decisions, and (e) 8% of the time on deploying strategies to improve team's culture. Naturally, these percentages will change depending on the project phase, but this snapshot illustrates how this structure works during the early design development phases.

3. TVD and the adoption of human-centered innovation strategies

All case studies followed a similar TVD process, which is comprehensively described by Melo et al. (2015). In this session, the specific items that refer to managing customer value and customer requirements are described. Beckman's "innovation cycle" described in the literature review was used here to provide a framework to analyze the findings. Below is a list of strategies observed in the projects, categorized according to the four quadrants of the innovation cycle:

a) Reflective observation and empathy building (observe and notice):
   - Hybrid team of owner stakeholders and industry practitioners engaged from early project stages. That allows project participants to build empathy and understand better the why behind requests, preferences, decisions, and also limitations or consequences of their requests;
   - A validation study that is carried out collaboratively by this hybrid team;
   - Owner stakeholders as an integral part of the team – i.e., managing PITs for idea creation, evaluation, and liaison with other stakeholders with a strong message around the expectations to focus on what is best for patients;
   - Active participation of key external stakeholders in idea creation (i.e., permitting agencies, inspector), who are dedicated exclusively to the project and act as an integral part of the team;
   - Extensive stakeholder consultation throughout the different phases of design, which in this case includes patients, users, donors, owner leadership, city community, regulatory agencies, etc.; and
   - ICDC Academy, a series of presentations by UCSF clinical staff and other critical stakeholders in the big room, allows the team to engage with them and ask questions about their work and expectations regarding the project. The academy generally starts at the end of validation and runs throughout the construction phase, allowing for empathy building by those working in the field. Interviewees have expressed that this emphasis supports team building as it creates a unified culture driven by a greater purpose.

b) Abstract conceptualization (a collective effort of framing and reframing the problem)
   - Multidisciplinary Project Innovation Teams with owner stakeholders' involvement, where most of the ideation process happens. Here ideas are discussed, often leading to a co-designed solution;
   - Multi-disciplinary innovation, which is (temporary) workshops set up anytime the team needs to extend the time spent on PITs to further frame and reframe the problem and solutions with a specific scope (these meetings can be initiated by any team member – including owner stakeholders); and
   - Some strategies help the team to set the boundaries for problem framing and reframing. Examples are: (a) cost modeling methods, (b) design constraints to support pre-fabrication and easiness of logistics and installation, (c) project priorities represented in the project Conditions of Satisfaction; and (d) defined priorities for the decision-making process that is collectively defined by the integrated team (or discussion of factors to be considered during CBA processes).

c) Active experimentation and validation (imagine and co-design)
   - Cloud-based Innovation Log, this is a tank of ideas that all team members have access to and can contribute with ideas;
   - Set-based design, used to mature certain areas where the team sees multiple options could bring similar benefits to the project;

- Immersive Design Events are examples of workshops held to dive deeper into the needs and preferences of clinical staff and validate some of the designer's early assumptions. Also in that category are patient surveys built around design options and virtual mock-ups built early to validate some operational workflows with staff;
- CBAs and A3s are used as methods for presenting and discussing ideas; and
- Physical mock-ups, virtual mock-ups, and virtual reality are used to validate ideas and assumptions.

d) Concrete experimentation (make and experiment)[4]

- Value engineering here means design options that were validated and decided on but had to be revisited as saving opportunities emerged, indicating that the team learned something new. Based on this new information, that design should be revisited.
- Continuous estimating was placed here to illustrate a similar point. Options are sometimes drawn first and only later sent to estimators for cost input, who provide feedback. The team then learns about new cost implications and revisits the design seeking alternative solutions.

The picture below represents the observed initiatives displayed in the four quadrants of the innovation cycle (adapted from Beckman, 2022). This picture also distinguishes between the strategies observed in these case studies and typical strategies used in the application of TVD.

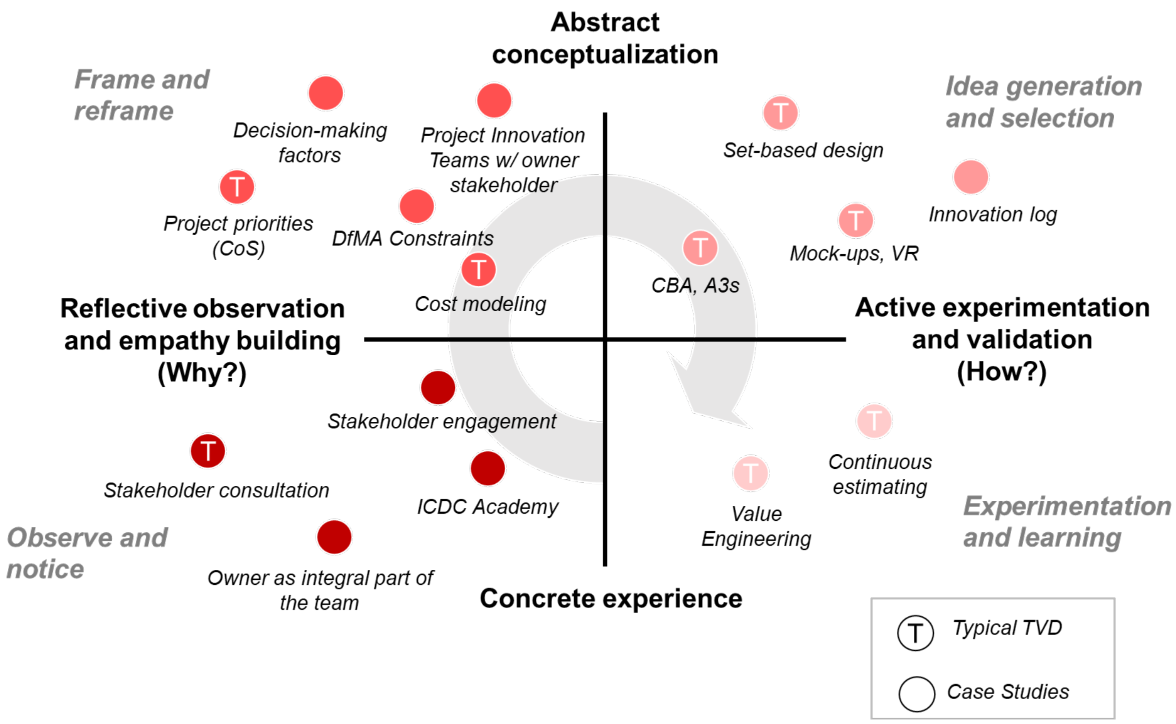

Figure 3: Human-centered innovation strategies used within TVD (Adapted from Beckman 2022)

DISCUSSION

Based on a human-centered approach to innovation proposed by Beckman (2022), the strategies to focus on and manage customer value were analyzed in the case studies. These cases illustrated mechanisms to engage customers in the crucial stages of the human-centered approach: (a) solution development (Quadrants 3 and 4) and (b) problem definition (Quadrants

[4] Concrete experimentation should be understood in this study as the crystallization of a design solution and subsequent documentation on the final set of drawings.

1 and 2). The examples ranged from typical approaches to more unique approaches. Some of the unique approaches include the ICDC academy, with the ultimate purpose of connecting people for empathy building. Another unique approach was the participation of owner team members in the day-to-day management of requirements capturing, idea generation, evaluation, and selection (as opposed to only participating in the evaluation and selection of ideas). In addition, other unique mechanisms were identified during the problem framing and reframing stage. For example, constraints that are discussed on a conceptual level, such as parameters for pre-fabrication, the project's agreed conditions of satisfaction, or even a high-level discussion about the factors to be considered during decision-making. Those serve as guardrails to support problem framing and reframing.

More traditional techniques and methods used on TVD were also observed. This study categorized continuous cost estimating and value engineering as steps pertaining to the fourth quadrant. The reason for that is because they often happen when there was a need to revisit a solution that was already generated or solve emerging issues based on new learnings before setting the final decision. Displaying these mechanisms on the innovation cycle enabled the realization that current best practices for TVD generally fall into the *"idea generation and selection"* and *"experimentation and learning"* categories of the innovation cycle, whereas the unique ones observed in this research can be placed in the *"observe and notice"* and *"frame and reframe"* categories of the cycle. This finding indicates that these unique ideas might bring a complementary perspective to the current best practices of TVD. Also, due to their focus on the "Why" and a deep understanding of customer needs, they represent a greater emphasis on value generation and provide evidence that these approaches can be successfully implemented within TVD while also achieving financial targets.

From a theoretical perspective, this research also corroborates with findings from many previous studies (Ballard, 2011; Bascoul et al., 2018; Parrish & Tommelein, 2009; Arroyo, 2014) that describe the benefits of adopting methods and techniques that support dialogue and the collective understanding of problems-solution space. Thus, building on previous research findings, this paper provides insights on how TVD adoption can be enhanced from the perspective of managing customer value, specifically in what relates to the use of methods and techniques that fall in the second generation of design theories.

CONCLUSIONS AND FUTURE RESEARCH

The research question that motivated this study was: How can we improve value management within target value design to focus more on customer value (along with steering a project to a target cost)? This paper aimed to answer that question by offering a perspective on managing human-centered innovation to focus on customer value during the application of TVD. The journey of UCSF Health to rethink its project delivery methods to focus on value included adopting several strategies related to a humanistic approach to design. This approach shaped how TVD is implemented in these case studies. Its analysis provided insights into complementary design and decision-making strategies traditionally used in TVD. In particular, the design strategies observed in this research expand TVD best practices to include participatory and empathic ways of understanding, framing, and reframing design problems. This research also provided evidence that these approaches can be successfully implemented within TVD to improve customer value without compromising the achievement of financial targets. Finally, this research shows that human aspects of design theories may bring underlying contributions to the construction management discipline, which might not be fully understood and deserves further investigation.

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SET-BASED DESIGN IN CONSTRUCTION PROJECTS: BENEFITS, DIFFICULTIES AND TRENDS

Karen Castañeda[1], Rodrigo F. Herrera[2], Omar Sánchez[3], and Guillermo Mejía[4]

ABSTRACT

Design processes generate inputs to plan and control the development of project construction processes. There is a growing interest in implementing design techniques involving various options to reach a systemic overview and select the best proposal. One such technique is Set-Based Design (SBD) which identifies and explores multiple design options simultaneously. Although several studies have been carried out focused on the SBD implementation in construction projects, there need to be more studies that synthesize the main findings to facilitate a proper implementation according to the different contexts. Considering this gap, this paper focuses on presenting a synthesis of SBD's benefits, difficulties, and trends in construction projects. The research method corresponds to a systematic literature review of a sample of 281 documents initially drawn from Scopus database and finally, with 32 documents screened, this study undertook the following stages. The research method has five stages: 1) scope definition; 2) searching of relevant documents; 3) document selection; 4) evidence collection, analysis, and synthesis; and 5) results report. The findings show a trend towards adopting the SBD technique for the design of structural elements of buildings and bridges. The three most frequently reported benefits of SBD adoption are: 1) transparent decision-making processes, 2) better collaboration in decision-making, and 3) better communication among designers. The three most frequently reported difficulties 1) inadequate organizational structure for the adoption of SBD, 2) lack of staff experience, 3) resistance to change in organizations.

KEYWORDS

Set-based design, point-based design, benefits, difficulties, trends, systematic review.

INTRODUCTION

The adoption of Lean Construction tools in the architecture, engineering and construction sector has increased considerably in recent years (Wong et al., 2009). Several studies show that the inclusion of Lean Construction tools in design processes increases product quality, because it promotes compliance with project requirements and increases the value expected by the client (Rischmoller et al., 2006). Nonetheless, if the project design fails, it can compromise the success and continuity of the project. The strong influence of design on construction projects is due to waiting times, rework, accidents, and other events that can result from design defects,

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which are identified only at the construction stage (Koskela et al., 2012). If a contractor identifies a design failure, he should request an adjustment or clarification from the designer and wait for a response. The designer can take a significant period to generate a response, which can result in deviations from planned schedules, budgets, and scope; phenomena that have been observed in construction projects around the world (Herrera et al., 2020). Therefore, it is necessary to study methodological and technological approaches that can contribute to improve the design processes. The design process of a construction project involves the interaction of professionals from different disciplines and various analyses to define the characteristics of the project components that meet the requirements and needs of project stakeholders (Herrera et al., 2021). The multidisciplinary nature of design and the associated volume of information generate complex systems to organize and manage (Hannapel & Vlahopoulos, 2014). Nonetheless, in most projects, design processes are based on linear methods that focus on the development of a single design alternative, which limits the possibility of achieving efficiency and generating value for the client.

Several studies have shown benefits of implementing SBD in design processes. For example, Chuquín et al. (2021b) applied a survey at the end of a design process with SBD, the findings showed that 72% believed that the quality of their work had increased, and rework had decreased. Besides, Chuquín et al. (2021a) conducted a survey of the usefulness of SBD among the participants of a case study of a high-rise building. The results showed that 70% of the respondents highlighted the usefulness of SBD and expressed their intention to adopt SBD in future projects. Additionally, Kerga et al. (2016) performed a systems dynamics model to simulate five design alternatives. The findings showed that SBD can contribute to reduce the average project duration by 25%, the total cost by 40%, and significantly improve the return on investment. As in the construction industry, SBD has shown benefits in design processes in other industries. Also, Yamada et al. (2016) performed SBD implementation to generate sustainable design alternatives of a laser printer. The results showed that the total price can be reduced by 18.7% to 36.8% compared to a conventional product, and the total amount of CO_2 emissions of the product can be reduced by 21.9% to 18.8%.

The potential of SBD to improve various design issues has generated interest among industry practitioners and researchers, which has been observed with the publication of several papers addressing the topic (Lee et al., 2012; Shallcross et al., 2020; Singer & Doerry, 2009). However, there is a lack of studies focused on compiling and synthesizing the main findings of SBD implementation in the design activities of construction projects. Therefore, this study has two aims: 1) to identify the benefits and difficulties of SBD adoption in construction projects, and 2) to synthesize the trends of SBD in the construction industry.

TRADITIONAL DESIGN BACKGROUND

Point-Based Design (PBD) has been characterized in the AEC industry as the traditional way of design. PBD is based on an initial design proposal that is progressively detailed. The degree of detail increases as design disciplines become more involved, a characteristic that can be considered ideal (Lee et al., 2012). However, on the one hand, the linearity of PBD compromises the efficiency of the process when a new design requirement arises. A scenario in which designers must perform extensive rework processes to adjust designs to the new requirement. On the other hand, the linear character leads to assume aspects of the design that can lead to issues of incompatibility, inconsistency, and inefficiency in the integration of project elements.

The limitations of the PBD approach have led industry practitioners and researchers to make efforts to adapt and improve techniques that involve the analysis of various design alternatives. In the design of construction projects, one of the techniques that has shown remarkable benefits is Set-Based Design (SBD), which can be assumed as a design management methodology of Lean thinking (Singer & Doerry, 2009). SBD is based on a set of alternatives that when properly combined lead to an efficient design solution, which is aligned with the client's requirements and project constraints (Toche et al., 2020). In the design of a building project based on SBD, the team of architects proposes a set of alternatives for the distribution of spaces and finishes that meet the client's requirements. The structural engineering team generates a set of structural system alternatives in accordance with the general characteristics of the project. Similarly, other design teams propose a set of alternatives, such as sanitary engineering, electrical engineering, sustainability, and others as required. The initial design alternatives are formulated at a low level of detail in order to promote efficiency in the process.

For the selection of the appropriate combination of alternatives, the SBD technique involves a set of objective-based tests that are related to the project requirements (Singer & Doerry, 2009; Toche et al., 2020). Therefore, some of the tests can be focused on objectives related to budgets, schedules, emissions, functionality, construction processes, and materials, among others. Thus, SBD may be adopted for the formulation and evaluation of design alternatives generated by one or more design disciplines of a project. The analysis of various alternatives leads to the adoption of methods to support decision-making processes. SBD integrates criteria evaluation factors for the selection of alternatives based on project requirements (Shallcross et al., 2020). These characteristics generate the need to integrate SBD with computational and methodological tools that support the generation and evaluation of design alternatives. Therefore, several studies have been carried out focused on the joint implementation of SBD and technological and methodological approaches, such as: building information modeling, value stream mapping, choosing by advantages, multi-criteria decision analysis, among others (Lee et al., 2012).

RESEARCH METHOD

For literature review, there are several methodologies, among which bibliometric analysis, meta-analysis and systematic review stand out. According to Donthu et al. (2021), the systematic review is recommended for samples up to 300 documents. Thus, the research method adopted corresponds to a systematic literature review, which focuses on identifying existing knowledge based on systematic procedures to answer a research question. Compared to other review methods, systematic review reduces subjectivity in the extraction of information and analysis of results, which is achieved through the evaluation of a set of inclusion/exclusion criteria for the selection of the sample documents. This study uses systematic review to identify benefits, difficulties, and trends of SBD in construction projects. Therefore, the research method was divided into five main stages: 1) scope definition; 2) searching of relevant documents; 3) document selection; 4) evidence collection, analysis, and synthesis; and 5) results' report. The scope definition was based on the research aims mentioned in the introduction section.

The search and selection of the sample focused on documents that offered the reliability of having undergone peer review processes, this reliability being a relevant factor for the selection of the search engine. Scopus provides this reliability and is considered a search engine that addresses a large number of areas of study in the field of research, so the use of other search engines in addition to Scopus can be considered as a complementary and equally important search. Thus, the search and collection of relevant documents was performed in the Scopus search engine using the following search equation: ("set-based design" OR "set based design" OR "set-based-design" OR "set based-design"). An initial sample of 273 documents was collected, including conference papers, articles, conference reviews, and reviews published between 1994 and 2022. In addition, considering the focus of the research, documents related to the research topic that are available in the IGLC database were included, with the same search equation. A second sample of 16 documents was collected, from which 8 documents repeated from Scopus were discarded, leaving a total of 281 documents.

The final document selection was carried out by applying two inclusion/exclusion criteria: 1) the paper addresses topics related to SBD methodology, and 2) the paper addresses topics related to SBD adoption in the construction industry. The criteria were evaluated by three researchers with knowledge of the topic studied and experience in the systematic review methodology. Each researcher evaluated the criteria individually, thus, for each document and criterion, "yes" was assigned if the document meets the criterion, and "no" if it does not. At the end of the evaluation, it was observed that in 10 of the 281 documents analyzed there was a difference in the evaluation results. Therefore, a meeting was held between the three researchers, and a consensus was reached. By applying the first criterion, 60 documents were discarded. Thus, a total of 221 documents were analyzed with the second criterion, of which 32 documents were selected, and 191 documents were discarded. Therefore, the evidence collection, analysis, and synthesis were performed by reading the resulting 32 documents selected on the basis of the two criteria. The information was collected and organized in an Excel table.

To collect and analyze the information from the selected sample, a detailed reading of each of the documents was carried out. Thus, benefits, difficulties and trends of SBD implementation in construction projects were identified. The information gathered was analyzed by three experts in the research topic. In addition, as part of the discussion of results, four categories were identified for the classification of complementary SBD tools. These categories are part of the added value provided by the group of experts (professionals in the construction industry with a doctorate degree and more than 10 years of experience) who, based on the approach of SBD complementary tools in the documents and the analysis of Lean tools vs. Lean objectives performed by Aslam et al. (2022), made the proposal of categories. Each expert related the SBD complementary tools to the categories, based on affinity and grouping exercises. As part of the classification exercise, the expert group held consensus meetings to discuss and eliminate variations between the complementary SBD tools and the categories. Finally, a frequency analysis has been carried out as part of the exploratory study and identification of the most adopted SBD complementary tools in the AEC industry.

RESULTS

This section presents the benefits, difficulties and trends of SBD adoption in construction projects, according to the analyzed sample. As a result of the research, 23 benefits, 22 difficulties and trends of SBD adoption were identified. The benefits and difficulties of adoption are presented through an absolute and relative frequency analysis. This frequency analysis provides a summary statistic, with which it is possible to compare the benefits and difficulties most frequently evidenced in the literature, as well as the weight of each benefit and difficulty within the set. This analysis could provide an impetus for SBD research in the AEC sector by presenting the results of research within the industry. Finally, a subsection of research trends and complementary approaches to SBD implementation in construction projects is presented. The approaches have been categorized according to their affinity by a group of experts in the research field.

BENEFITS OF SET-BASED DESIGN ADOPTION

Table 1 shows the top-10 most frequently reported SBD benefits in construction projects. The adoption of SBD promotes transparent decision-making processes, based on the selection of design alternatives that focus on satisfying project requirements. This feature helps to prevent decisions from being affected by the particular interests of the designers (Mathern et al., 2019; Parrish & Tommelein, 2009; Sahadevan & Varghese, 2019). Therefore, one of the most frequently reported benefit is 'transparent decision-making processes' (B_1). With the same frequency, the benefit 'better collaboration in decision-making' (B_2) was identified, which is obtained from the collaborative process of analysis and proposal of design alternatives involved in the SBD adoption (Lee & Cho, 2012; Lee et al., 2010). A process that requires the joint participation of the professionals involved, on the one hand, to verify the compatibility and coherence between the options analyzed. On the other hand, to select the combination of alternatives that best meets the requirements of the project.

Table 1. Benefits of SBD adoption in the construction industry.

Id	Benefits	Absolute frequency	Relative frequency (n=32)	References*
B_1	Transparent decision-making processes	10	31.3%	10, 11, 12, 13, 15, 16, 18, 22, 26, 30
B_2	Better collaboration in decision-making	9	28.1%	7, 8, 10, 14, 18, 19, 20, 25, 26
B_3	Better communication among designers	7	21.9%	7, 13, 19, 21, 22, 23, 26
B_4	Improvement of the design solution	7	21.9%	1, 5, 11, 14, 23, 25, 26
B_5	Analysis of various design alternatives	6	18.8%	7, 8, 10, 13, 21, 22
B_6	Increased design solution functionality	6	18.8%	4, 9, 10, 21, 26, 28
B_7	Reuse of design knowledge	6	18.8%	10, 12, 14, 15, 26, 28
B_8	Reduction of rework	6	18.8%	5, 15, 20, 24, 26, 27
B_9	Increased design solution efficiency	5	15.6%	7, 8, 20, 23, 28
B_{10}	Promotes sustainability in the projects	4	12.5%	3, 10, 16, 17

*1. (Chuquín et al., 2021b), 2. (Chuquín et al., 2021a), 3. (Gomez & Rameson, 2019), 4. (Inoue, Takahashi, et al., 2013), 5. (Zoya Kpamma & Adjei-Kumi, 2011), 6. (Kim & Lee, 2010), 7. (Lee & Cho, 2012), 8. (Lee et al., 2012), 9. (Inoue, Nahm, et al., 2013), 10. (Mathern et al., 2019), 11. (Padala & Maheswari, 2017), 12. (Parrish & Tommelein, 2009), 13. (Parrish et al., 2008b), 14. (Parrish et al., 2007), 15. (Parrish et al., 2008a), 16. (Mathern et al., 2018), 17. (Rempling et al., 2019), 18. (Sahadevan & Varghese, 2019), 19. (Tauriainen et al., 2016), 20. (Tuholski & Tommelein, 2010), 21. (Unal, Eeri, et al., 2017), 22. (Wong et al., 2009), 23. (Wong et al., 2007), 24. (Lee et al., 2012), 25. (Lee et al., 2010), 26. (Arroyo & Long, 2018), 27. (Ballard, 2000), 28. (Haymaker et al., 2013), 29. (Knotten et al., 2014), and 30. (Nguyen et al., 2008).

The third most frequent benefit is 'analysis of various design alternatives' (B_3). Some characteristics of construction projects, such as unique and multidisciplinary character, complexity and uncertainty, and required financial capital make the analysis of various design options indispensable during the early stages of the projects (Chuquín et al., 2021a; Rempling et al., 2019). Therefore, benefit B_3 has a positive effect on ensuring that the design solution generates the value desired by the client and satisfies the requirements that gave rise to the project. The fourth benefit is 'better communication among designers' (B_3), which is integrated with benefits B_1, B_2, and B_5 considering that communication is transversal to the decision making and collaboration processes among design teams (Tauriainen et al., 2016; Unal, Eeri, et al., 2017; Wong et al., 2009). Thus, communication favors the proposal and analysis of various design options. The fifth benefit is 'improvement of the design solution' which is obtained by exploring a space of possible design solutions, from which the team has the possibility to choose the alternative that best aligns with the project requirements.

DIFFICULTIES OF SET-BASED DESIGN ADOPTION

Table 2 shows the top-10 most frequently reported SBD adoption difficulties. The 'inadequate organizational structure for the adoption of SBD' (C_1) is the most reported difficulty, which is related to the staffing requirements and organizational structure in the design disciplines of a construction project (Chuquín et al., 2021b; Gomez & Rameson, 2019). C_1 has a major impact on some organizations because it is common to subcontract some of the design disciplines with specialized firms (Hassan & Le, 2021). Subcontracting means that two or more firms must adapt their workflows to integrate design teams according to SBD principles. The second difficulties is 'lack of staff experience' (C_2) which is based on the knowledge and experience needed to adopt SBD by the professionals involved in the design of a construction project (Lee et al., 2010; Zoya Kpamma & Adjei-Kumi, 2011). The emerging nature of SBD in the construction industry leads to a lack of human talent with experience and knowledge in the adoption of SBD. In addition, there is a lack of efforts focused on including SBD in education programs related to the training of professionals in charge of the design of construction projects.

Table 2. Difficulties of SBD adoption in the construction industry.

Id	Difficulties	Absolute frequency	Relative frequency (n=32)	References*
C_1	Inadequate organizational structure for the adoption of SBD	7	21.9%	1, 3, 4, 11, 15, 18, 19
C_2	Lack of staff experience	6	18.8%	1, 4, 9, 11, 21, 26
C_3	Resistance to change in organizations	6	18.8%	1, 3, 4, 26, 27, 29
C_4	Lack of information compatibility between design disciplines	5	15.6%	3, 12, 15, 19, 28
C_5	Limited information to propose design alternatives	4	12.5%	2, 6, 12, 17
C_6	Greater design effort	4	12.5%	7, 12, 13, 16
C_7	Difficulty in managing design processes	4	12.5%	4, 7, 19, 31
C_8	Barriers related to the legal framework	3	9.4%	4, 7, 11
C_9	High dependence on designer's judgment in decision making	3	9.4%	7, 8, 9
C_{10}	Increased design time due to more alternatives	3	9.4%	7, 9, 26

*1. Notation according to Table 1.

'Limited information to propose design alternatives' (C_3) is the third most frequently reported difficulty. The adoption of SBD requires the availability of the information required for the proposal and analysis of design alternatives (Parrish et al., 2008a; Unal, Eeri, et al., 2017). The complexity of the interactions between design disciplines and the multidisciplinary nature of the teams make it difficult to provide, at the right time, the necessary information to propose design alternatives. 'Greater design effort' (C_6) has the same frequency as C_5. Proposing and analyzing several alternatives instead of a single design alternative requires more effort from the design team (Mathern et al., 2018, 2019). However, the consideration of a greater number of design options contributes to the 'reduction of rework' (B_8) and the 'reduction in design times' (B_{12}). Therefore, investment in increased effort by designers could generate positive return on investment (ROI) rates.

Despite the fact that 'Lack of information compatibility between design disciplines' (C_4) does not have the same frequency as C_5 and C_6. The various engineering processes carried out in the design stage of a construction project lead designers to use different tools for the information capture, processing and analysis (Gomez & Rameson, 2019; W. Lee et al., 2010). The diversity of tools and methods has generated difficulties in the integration of information due to the difficulty in making information compatible between design disciplines. Despite the efforts for the adoption of methodologies such as Builiding Information Modeling (BIM) with information exchanges based on Industry Foundation Classes (IFC), difficulties are observed in the exchange of information between design disciplines, which affects the efficient adoption of SBD (Lee et al., 2012)

DISCUSSION

COMPLEMENTARY APPROACHES TO SET-BASED DESIGN

This study found that the SBD is boosted when complementary design management techniques are used. This section summarizes these techniques in four categories: 1) information and process management, 2) decision making, 3) analysis tools, and 4) design (see Table 3).

Table 3. Complementary approaches of SBD adoption in the construction industry.

ID	Category	Complementary SBD		Fr.	Relative frequency (n=32)
1	Information and process management	Building Information Modeling	BIM	6	18.8%
2		Value Stream Mapping	VSM	2	6.3%
3		Design Structure Matrix	DSM	3	9.4%
4		Big Room	Big room	1	3.1%
5		Activity Cycle Diagrams	ACD	1	3.1%
6		Lean Project Delivery	LPD	1	3.1%
7		Lean Project Delivery System	LPDS	1	3.2%
8		Last Planner System	LPS	1	3.2%
9	Decision making	Multi-Criteria Decision Analysis	MCDA	6	21.9%
10		Choosing by Advantages	CBA	6	18.8%
11		Analytic Hierarchy Process	AHP	3	9.4%
12		Group Decision Making	GDM	1	3.1%
13		Sequential Decision Process	SDP	1	3.1%
14		Design by Shopping	DBS	1	3.1%
15		Knotworking	knotworking	1	3.1%
16		A3 reports	A3 reports	1	3.1%
17		Belief Propagation	BP	1	3.1%
18	Analysis tools	Finite Element Method	FEM	3	9.4%
19		Artificial Intelligence	IA	1	3.1%
20		Monte Carlo Analysis	MC	1	3.1%
21		Genetic Algorithm	NSGA	1	3.1%
22		Space Syntax Analysis	SSA	1	3.1%
23		Simulation	Simulation	1	3.1%
24	Design	Target Value Design	TVD	5	15.6%
25		Parametric Design	PD	2	6.3%
26		Depthmap	Depthmap	1	3.1%
27		Set-Based Parametric Design	SBPD	1	3.1%
28		SetPlan	SetPlan	1	3.1%
29		Tekla Structures 14.0	TS 14.0	1	3.1%
30		Lean design	LD	1	3.1%

The SBD technique can be integrated with various complementary approaches to improve the information management processes of the design of construction projects. Therefore, there is a growing interest in integrating SBD with approaches to improve information management processes, such as: Building Information Modeling, Value Stream Mapping, Design Structure Matrix, and others (see Table 3). It is observed that BIM is one of the complementary approaches to SBD that has a higher frequency within the Information and process management category. Studies that have addressed the integration of BIM and SBD have focused on the development of improvement tools for the creation of alternatives in various fields, such as constructability, structural safety, economic feasibility, design management, and shared understanding, among others (Lee & Cho, 2012; Tauriainen et al., 2016; Tuholski & Tommelein, 2010; Wong et al., 2009). Integrating BIM and SBD makes it possible to improve information flows and communication during design activities that are developed by professionals from different disciplines during the early stages of projects. Improving information management processes has a positive impact on the development of construction projects considering that projects involve considerable volumes of information during the design stage.

MCDA is the most commonly adopted complementary tool to SBD in decision-making processes. Evidence of MCDA adoption was identified mainly in the development of road infrastructure projects. Some of the approaches, on the one hand, are oriented to support the selection of strategies for the development of facilities in road projects, evaluate design processes, support decision making, analyze constructability concepts and sustainability criteria, in the structural design of bridges. On the other hand, MCDA has adopted to optimize the structural design of buildings based on sustainability criteria and design alternatives among others (Mathern et al., 2018, 2019; Padala & Maheswari, 2017). Thus, the evaluation of various design alternatives using the SBD tool leads to the need to integrate tools to support the decision-making processes that focus on the evaluation and selection of design alternatives. Hence, there is a trend towards the joint adoption of SBD with techniques that support the decision-making processes during the analysis of alternatives, such as: Multi-Criteria Decision Analysis, Choosing by Advantages, Analytic Hierarchy Process, and others.

The multidisciplinary nature of a construction project means that the design process integrates various engineering analyses that require specialized techniques to carry out the design of the components of a construction project. Hence, there is a trend towards the integration of SBD with tools that can improve and automate the design processes, such as: Finite Element Method, Artificial Intelligence, Monte Carlo Analysis, and others (see Table 3). In turn, these tools can be complemented with design techniques, such as: Target Value Design, Parametric Design, and others. It is noteworthy that in the design category, the TVD approach is the one with the highest frequency, which is related to the complementary nature of the two tools. On the one hand, SBD focuses on the proposal and selection of alternatives, and on the other hand, TVD focuses on the development of the design from a set of budgetary requirements. Therefore, integrating TVD and SBD has a high potential to promote the generation of value for the client from the analysis of several design alternatives that are framed in a budgetary requirement. The findings show that the joint adoption of SBS and TVD has been focused on building, road infrastructure, and bridge projects (Arroyo & Long, 2018; Gomez & Rameson, 2019; Kim & Lee, 2010). Despite the existing studies, it is evident that there are several knowledge gaps, which can be analyzed from the moderate number of documents and the few fields of knowledge that have been focused on: sustainable development, design and evaluation of spaces, and others. Furthermore, there is a lack of studies focused on design and information workflows that facilitate the joint adoption of SBD with complementary tools by the design disciplines that interact in a construction project. Thus, it is expected that in the coming years there will be a growing interest in the development of computational tools based on the integration of SBD principles and complementary approaches specialized in the design of building components.

The adoption of SBD can significantly contribute to improve various aspects of the design of construction projects. Therefore, in the construction industry, it is crucial that researchers and practitioners undertake actions focused on the development of works that make possible the implementation of SBD in the different design disciplines that interact in a construction project. The integration of SBD with emerging tools and methodologies such as: BIM, Multi-Criteria Decision Analysis, Target Value Design, and others (see Table 3) can contribute to improve the decision-making processes that are carried out during the design activities of a construction project. Despite its potential, the findings of this study show that there are several knowledge gaps in the characterization of SBD integration with various complementary approaches. Therefore, it is expected that the coming years will see an increasing number of studies focused on characterizing SBD integration with methodological and technological approaches that can be conducive to leveraging SBD principles, which is focused on the requirements of construction projects.

KNOWLEDGE GAPS AND TRENDS OF SET-BASED DESIGN

There are knowledge gaps of SBD adoption in different types of construction projects. From the set of documents analyzed (n=32; 100%), the types of construction projects identified with SBD adoption were: buildings (n=18; 56.3%), bridges (n=5; 15.6%), road infrastructure (n=3; 9.4%), and other projects (n=6; 18.8%). Hence, there is evidence of a gap in the adoption of SDB in horizontal projects, in which the characteristics of SBD can contribute to obtaining more efficient and sustainable projects. In road projects, SBD can contribute to the analysis and selection of road alignment alternatives based on a set of requirements and limitations defined for the project. Once the alignment is selected, SDB can be adopted to analyze and define a space of possible design configurations, from which designers can select the one that best aligns with the needs of the project. Although there has been a greater adoption of SBD in vertical projects, it has focused mainly on the design of structural elements. Therefore, there are gaps in the adoption of SBD in other design disciplines that are crucial, such as: utility service networks, geotechnics, architecture, HVAC, and sustainability, among others. In addition, there is a lack of studies focused on the analysis and selection of vertical project design alternatives with a multidisciplinary and multi-criteria approach.

Efforts are being made to integrate SBD with various methodological and technological approaches to support the design processes of construction projects (see Table 3). However, the results show gaps in the joint adoption of SBD with systems based on artificial intelligence and cloud computing. A situation that is similar to the joint adoption of SBD with workflows based on virtual reality, internet of things, big-data, machine learning, and others. Therefore, it is expected that in the coming years industry practitioners and researchers will make efforts to integrate SBD principles with construction 4.0 approaches. An integration that has a high potential to automate and improve the efficiency of design processes for construction projects.

CONCLUSIONS

The theoretical contribution of this study is the identification of benefits, difficulties, and trends of the adoption of SDB in construction projects. The research method was based on a systematic literature review of an initial sample of 281 documents. The five most frequently reported benefits of SBD adoption are: 1) transparent decision-making processes (B_1), 2) better collaboration in decision-making (B_2), 3) better communication among designers (B_3), 4) improvement of the design solution (B_4), and 5) analysis of various design alternatives (B_5) (see Table 1). The results show a wide potential of SBD to improve various construction project design issues, however, there are some difficulties that have limited the adoption of SBD in the construction industry. The five most frequently reported SBD adoption difficulties are: 1) inadequate organizational structure for the adoption of SBD (C_1), 2) lack of staff experience (C_2), 3) resistance to change in organizations (C_3), 4) lack of information compatibility between design disciplines (C_4), and 5) limited information to propose design alternatives (C_5) (see Table 3). It should be noted that the contributions of this study are based on a structured review of the literature rather than data obtained through the adoption of SBD in any activity of the life cycle of construction projects. Thus, it is expected that with the emergence of new studies, modifications in benefits, difficulties and trends will occur.

Several of the identified difficulties can be addressed by integrating SBD with approaches that encourage the automation of design processes based on various alternatives. Therefore, there is a trend towards the integration of SBD with complementary technological and methodological approaches to support the processes of proposal and analysis of design alternatives. Among the complementary approaches identified, the following stand out: building information modeling, multi-criteria decision analysis, choosing by advantages, target value design, and finite element method, among others. Therefore, it is expected that in the coming years SBD adoption research will focus on proposing, adopting, and improving design process workflows from the integration of both the complementary tools identified (see Table 3) as well as emerging approaches related to construction 4.0.

The main limitations of this study are: 1) the review's focus on the adoption of SBD in the construction industry without including other industries; 2) the lack of documents from databases other than Scopus; 3) the scope of the review focused on the benefits, difficulties, and trends of SBD, leaving aside other topics of interest; 4) the method of analysis is based on a frequency analysis due to the moderate number of documents that address the adoption of SBD in construction projects, therefore, this study can be classified as exploratory; and 5) all the analyzed documents are assumed to be on equal conditions, which is motivated by the exploratory nature of most of the existing studies that address the adoption of SBD in construction projects. Therefore, future work could focus on 1) review and analyze SDB developments in other industries, 2) update the review presented with documents published in other databases, 3) review SBD developments in the construction industry with complementary approaches to the one presented in this study (see Table 3); 4) adopt more sophisticated analysis methods to study the adoption of SBD in construction projects; and 5) propose approaches that integrate SBD theoretical principles and tools based on artificial intelligence to facilitate the proposal and analysis of design alternatives.

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PLANNED PERCENTAGE COMPLETED IN CONSTRUCTION – A QUANTITATIVE REVIEW OF LITERATURE

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ABSTRACT

Although several systematic literature reviews have focused on the Last Planner® system (LPS) and lean construction, few reviews have focused solely on the planned percentage completed (PPC) value. In this light, the present quantitative literature review aims to synthesize individual PPC-related studies from around the world. The research data consisted of 36 peer-reviewed research articles and conference papers published between 1998 and 2021; in these, PPC values were presented such that they could be collected and analyzed quantitatively. As a main finding, a statistically significant difference was observed between the mean PPC values presented in studies published in lean-focused journals and other peer-reviewed journals. The mean PPC values published in lean-focused journals were lower than those published in other peer-reviewed journals. This may indicate that results with higher PPCs are selected for other peer-reviewed publications; therefore, a potential publication bias should be investigated further. The study also revealed mean PPC values over time and geography, thereby enabling an evaluation of the construction industry's global progress by using PPC values as a benchmark.

KEYWORDS

lean construction, last planner, planned percentage completed (PPC), literature review.

INTRODUCTION

The Last Planner® system (LPS) is a planning system that has been developed in lean construction. Unlike in traditional scheduling, LPS emphasizes the role of the "last planner," namely, the foreman (or last person before task execution) who is as close as possible to the task, in production planning (Ballard, 2000). According to Ballard (2000), the key to the production planning system is a good definition of the task, selection of the right work order and workload, and reasonableness of the work task chosen to be implemented (i.e., can it and should it be done?). Planned percentage completed (PPC) is a quantitative measure calculated as the number of planned activities executed divided by the total number of planned activities. According to Ballard and Tommelein (2016), the PPC value used in the LPS is considered a measure of workflow reliability, a measure that correlates with productivity and project progress, and a measure of a team's ability to reliably plan and execute work. PPC is also often considered a visual illustration of the reliability of the promises made by the project parties to each other (Koskela *et al*., 2010).

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Researchers broadly agree that the key to measuring the PPC in LPS is the measurement of the reliability of the parties' promises (Howell *et al*., 2004; Fauchier & Alves, 2013). The PPC value is often used in research and practice related to LPS and lean construction, although a holistic examination of PPC values in individual studies is limited. Aslam *et al*. (2020) conducted an extensive literature review of LPS-related studies between 1992 and 2019 and presented mean PPC values from 16 cases. Based on these case studies, they estimated that the average PPC value is approximately 68%, and they stated that this was below their expectations. Accordingly, they proposed that finding and removing the main barriers in LPS would improve the PPC. Singh and Kumar (2020) reviewed literature from 2008 to 2018 focusing on tools and methods of lean construction but collected no PPC information. Babalola *et al*. (2019) reviewed lean construction literature from 1930 to 2018 with a focus on lean construction practices and identified PPC, although they did not collect any related evidence. Fernandez-Solis *et al*. (2013) conducted a systematic literature review of 26 case studies from 2000 to 2009 that focused on how practitioners have used LPS methods, although they did not collect any PPC values.

Although some studies have focused only on the PPC, this systematic literature review of LPS and PPC shows that a more comprehensive sample of research papers that present the PPC value is possible. This study differs from previous ones in that it analyzed PPC from a larger set of articles and over a longer period. In addition, it aimed to take a meta-view by comparing PPC between journals focused on lean and other peer-reviewed journals. We also assessed the geographical differences in PPC in our study. Most similar studies, such as that by Aslam *et al.* (2020), focused on the project-specific PPC as a single value but not on its variation over the course of the study; the present study highlights this point more explicitly than previous studies did. Because the PPC is a fundamental metric in the use of LPS, this study systematically explores a substantial number of studies that presented PPC values and presents a broad view of PPC values recorded worldwide and over time.

METHODS

The heterogeneity of the published research and the prominence of case studies in LPS research hinder the use of statistical analysis, such as meta-analysis. Instead of using statistical analysis, a quantitative literature review that is applicable to incoherent research data was chosen as the research method (Pickering & Byrne, 2014). In this method, the results of individual studies are combined to focus on finding similarities, differences, or other interesting findings that are not visible in individual studies but are observable from the combined set of several studies. However, because the PPC is a number, these differences are analyzed and discussed in this study mainly from a quantitative viewpoint.

The search strategy was primarily aimed at LPS-related studies, because information related to the PPC, which is the focus of this study, was assumed to be found in these studies. Therefore, the Last Planner System alone was used as a search term. Notably, the term "PPC" is also used in cancer research and is a common abbreviation for "production planning and control"; therefore, PPC as a search term would have produced many incorrect and unnecessary search results. In this light, first, the search term "Last Planner System" was used, and then, papers with the PPC values of the method were screened. The researchers searched for LPS-related studies in two research databases: Scopus and Google Scholar. Information was collected between 2020 and 2022, first as separate targeted search events and later using the continuous alert functionality of the Scopus database. Data were collected using the search term "Last Planner" and 551 research articles, review papers, books chapters, and books were identified. The researchers downloaded the papers to which they had either open access or access through the university's library service (including paywall journals). The literature search strategy is presented in Figure 1.

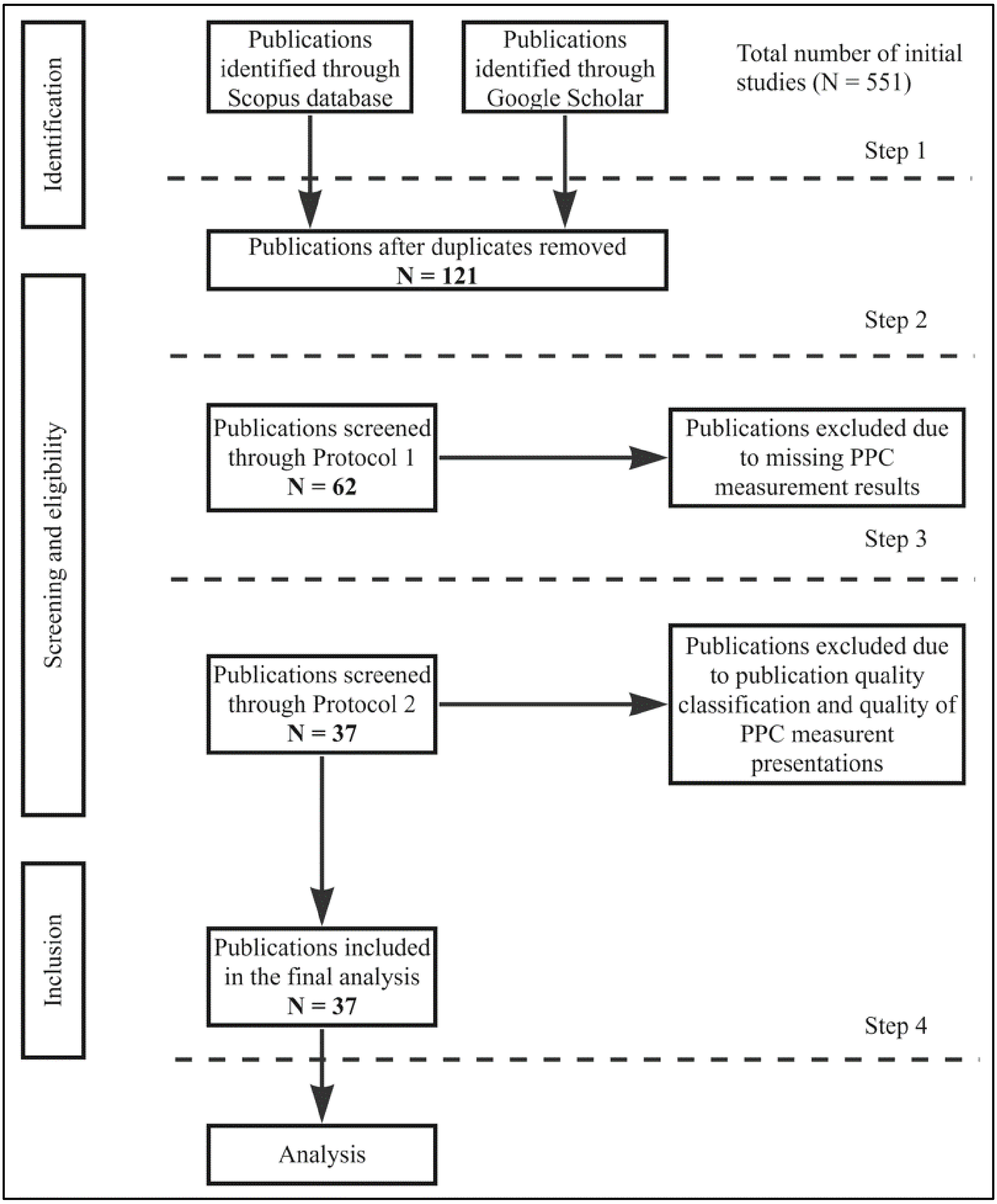

Figure 1: Literature search strategy.

In the first screening step, the researchers included only research articles and conference papers while also removing possible duplicates from different databases. Therefore, no book, part of a book, guidebooks, or industry reports about LPS were included. In the first step, 121 articles were processed. In the second step, the researchers scanned the research articles and searched for articles in which PPC values were presented in text, tables, or graphs; 62 such articles were found. In the third step, the researchers focused on the quality of the research and determined whether the research results were genuine results from actual case studies, action research, or runs from various project databases. All simulations, theoretical modelling, and design-related articles that included PPC results were also excluded. The quality of the study results was screened in this context, from which factors such as low-quality figures and tables or insufficient data were unclear. At this stage, articles that had been published in predatory journals were also excluded. After these screening steps, 37 peer-reviewed research articles and scientific conference papers were included in the final analysis.

In the analysis phase, basic information was collected from the research articles, such as the names of the authors, journal, and publisher; year of publication; country in which research data were collected; research method; and category to which the publication belonged. Two categories were defined: articles published in lean-specific scientific journals or peer-reviewed conferences and articles published in other peer-reviewed journals in the construction industry. Numerical data related to PPC were also collected from the articles, such as the mean, maximum, and minimum PPC values and their standard deviation. Regarding the duration of measurements of PPC values, we collected the number of PPC data points and the duration of the data collection process (in weeks). Information was collected from the text, tables, and figures of the articles. Data were stored and analyzed using Excel spreadsheets and Minitab 19 statistical software.

FINDINGS

The articles selected for the study are presented in Table 1. For each study, this table lists the mean (MeanPPC), maximum (MaxPPC), and minimum (MinPPC) PPC values and their standard deviation (StdPPC) as collected in the original study or calculated by the authors of the present study. For each study, the research method, geographic location, and information source were also collected (i.e., whether the PPC value was obtained from the text, tables, or figures of the study). In the table, the studies are presented in chronological order, and whether the study belongs to lean-focused publications ("LFB") or other peer-reviewed publications ("Other") is shown on the left-hand side next to the code. The code is a unique identification number (e.g., "33") assigned to a single study at the beginning of the study, and it contains subnumbers (e.g., "51.1") if the study has several cases in which a PPC value is presented. The abbreviation "Dat" implies the number of data points in the table (i.e., number of PPC measurements presented in the study), and the abbreviation "Dur" implies the duration of the study in weeks.

Table 1. Reviewed articles and research data.

Code	LFB	Other	Mean PPC	Max PPC	Min PPC	Std PPC	Dat.	Dur.	Method	Country	Data type	Reference
33	X		84.8	100.0	75.0	8.4	9	9	Case study	Brazil	Figure	Junior *et al.*, 1998
51.1		X	64.1	86.0	44.0	12.3	11	11	Dissertation	USA	Table & Figure	Ballard, 2000
51.2			57.1	71.0	46.0	8.1	10	10				
51.3			75.5	100.0	25.0	20.3	41	41				
51.4			84.0	93.8	51.3	8.8	27	27				
51.5			87.8	100.0	60.0	13.1	19	19				
43	X		61.0	N.A.	N.A.	N.A.	1	N.A.	Action research	Chile	Figure	Alarcón *et al.*, 2002
36	X		77.4	88.0	63.0	7.2	10	2	Work sampling	USA	Text & Figure	Chitla & Abdelhamid, 2003
47	X		70.0	N.A.	N.A.	11.4	N.A.	N.A.	Data mining	Brazil	Table	Bortolazza *et al.*, 2005
58.1	X		75.3	N.A.	N.A.	N.A.	3	12	Case study	South Korea	Text	Kim & Jang, 2005
58.2			74.0	N.A.	N.A.	N.A.	3	12				
60		X	64.0	90.0	40.0	16.5	11	11	Case study	USA	Figure	Beary & Abdelhamid, 2005
89	X		75.3	95.6	44.0	15.6	20	20	Case study	USA	Figure	Salem *et al.*, 2005
65	X		70.4	93	38	11.99	N.A.	N.A.	Data mining	Brazil	Table & Figure	Bortolazza, & Formoso, 2006
93		X	76	N.A.	N.A.	N.A.	N.A.	N.A.	Case study	USA	Text	Salem *et al.*, 2006
108.1	X		64.5	90.0	40.0	16.5	11	11	Case study	Not mentioned	Figure	Beary & Abdelhamid, 2006
108.2			76.1	100.0	48.0	16.8	9	9				
57	X		68.6	80.0	54.0	9.0	24	24	Case study	Not mentioned	Figure	Jang & Kim, 2007
81	X		51.1	62.5	33.3	9.4	13	13	Case study	Chile	Table & Figure	González *et al.*, 2007
16.1	X		86.3	100.0	63.0	8.3	53	53	Case study	Not mentioned	Figure	Jang & Kim, 2008
16.2	X		84.0	100.0	65.0	8.6	53	53				
96	X		76.3	100.0	23.0	18.6	71	71	Case study	Not mentioned	Figure	Liu & Ballard, 2008
23.1	X		81.7	100.0	69.0	6.7	18	18	Case study	Saudi Arabia	Figure	AlSehaimi,*et al.*, 2009
23.2			74.3	83.0	42.0	10.4	17	17				
55	X		76.03	100	22.14	N.A.	N.A.	N.A.	Data mining	Brazil	Table	Formoso & Moura, 2009
83	X		60.8	87.5	23.0	19.1	13	13	Action research	Norway	Figure	Kalsaas, *et al.*, 2009
100.1	X		51.4	90.0	20.0	17.2	36	36	Case study	Not mentioned	Figure	Olano *et al.*, 2009
100.2			66.2	90.0	27.0	16.8	37	37				
106	X		78	N.A.	N.A.	N.A.	N.A.	N.A.	Case study	Finland	Text	Seppänen *et al.*, 2010
14	X		67.0	93.0	56.0	7.1	33	33	Data mining	Chile	Figure	Alarcón *et al.*, 2005
45		X	75.6	100.0	0.0	20.5	106	106	Case study	USA	Figure	Liu *et al.*, 2011
21	X		89.4	98.0	70.0	8.7	10	10	Action research	Nigeria	Figure	Adamu & Howell, 2012
42.1	X		71.9	N.A.	N.A.	16.9	N.A.	N.A.	Case study	Not mentioned	Table & Figure	Alarcón & Zegarra, 2012
42.2			68.7	N.A.	N.A.	20.9	26	26				
42.3			57.7	N.A.	N.A.	23.5	N.A.	N.A.				
42.4			56.1	N.A.	N.A.	34.1	N.A.	N.A.				
42.5			58	N.A.	N.A.	17.8	18	18				
104.1	X		72.6	92.0	55.0	8.1	28	56	Case study	USA	Figure	Hamzeh *et al.* 2012
104.2			77.7	100.0	51.0	15.5	23	46				
18	X		83.2	100.0	32.0	15.8	29	29	Case study	Peru	Figure	Rosas, 2013
71	X		75.1	100.0	40.0	15.3	22	22	Design science research	Nigeria	Figure	Ahiakwo *et al.*, 2013
75	X		87.4	95.0	75.0	3.8	50	50	Case study	USA	Table	Hamzeh & Aridi, 2013
78.1	X		58	N.A.	N.A.	N.A.	17	17	Case study	Peru	Table	Pereira *et al.*, 2013
78.2			50.6	N.A.	N.A.	N.A.	17	17		Portugal		
102.1	X		71.9	N.A.	N.A.	16.9	26	26	Case study	Peru & Chile	Table & Figure	Zegarra & Alarcón, 2013
102.2			68.7	N.A.	N.A.	20.9	26	26				
102.3			57.7	N.A.	N.A.	23.5	26	26				
102.4			56.1	N.A.	N.A.	34.1	26	26				
102.5			58.0	N.A.	N.A.	17.8	26	26				
73.1		X	82.1	100.0	68.0	7.2	18	18	Action research	Saudi Arabia	Figure	AlSehaimi *et al.*, 2014
73.2			73.9	85.0	43.0	10.1	18	18				
94	X		62.7	81.0	40.0	11.6	19	19	Case study	India	Figure	Vaidyanathan *et al.*, 2015
50	X		43.7	76.0	17.0	15.1	30	38	Case study	Marocco	Figure	Hicham *et al.*, 2016
59.1		X	61.5	81.0	33.0	12.4	36	36	Case study	Finland	Figure	Sacks *et al.*, 2017
59.2			94.4	100.0	82.0	5.1	19	19		USA		
59.3			93.9	99.0	87.0	3.1	19	19		USA		
59.4			86.5	95.0	80.0	3.3	19	19		Finland		
68.1		X	54.4	89.0	0.0	23.0	10	10	Dissertation	UK	Figure	Daniel, 2017
68.2			82.0	99.0	47.0	11.8	20	20				
30		X	78.0	100.0	15.0	19.1	21	21	Action research	Finland	Figure	Elfving, 2021
121		X	80.7	100.0	61.0	9.1	110	113	Design science research	USA	Figure	Hamzeh *et al.*, 2019

The reviewed studies were published between 1998 and 2021. The highest number of studies in which PPC values are presented (26 out of 37) were published between 2005 and 2013. Geographically, the reviewed articles containing PPC values were mainly from South and North America and Western Europe. Africa and Asia accounted for three and four studies, respectively. Further, no studies were from large regions such as China, Russia, Australia, Canada, and Central and Eastern Europe. The geographical locations in which the reviewed articles were published are shown in Figure 2.

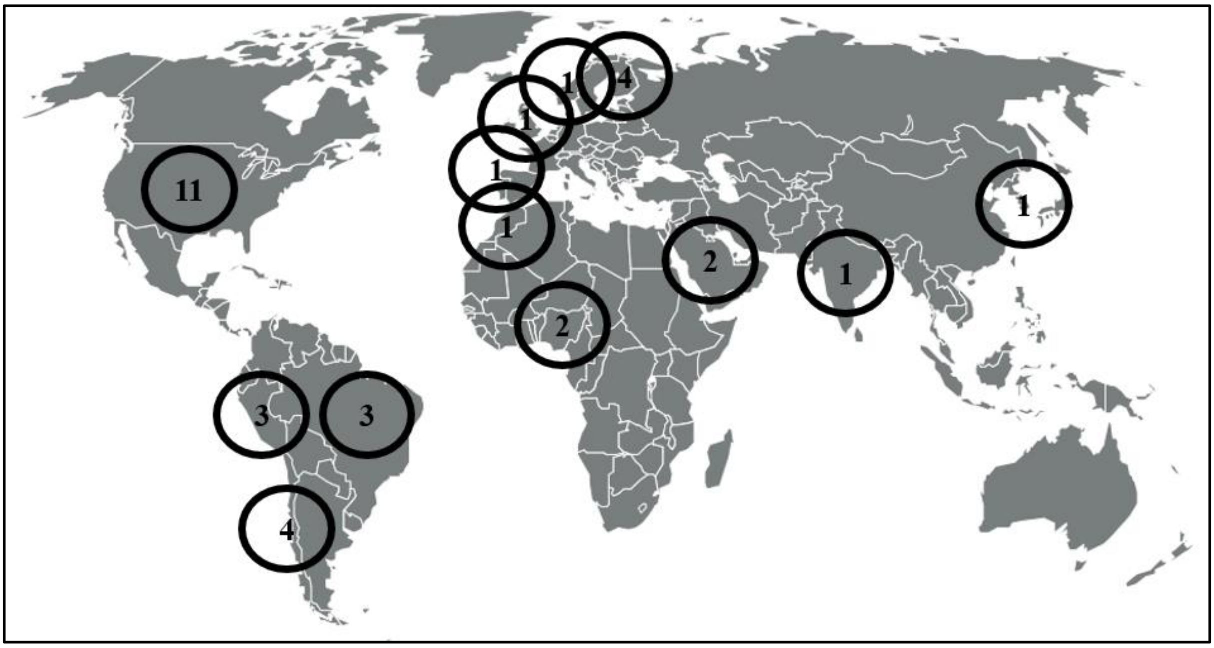

Figure 2: Geographical locations in which reviewed articles were published.

PPC measurements were performed for an average duration of 28 weeks, and the longest study lasted for 113 weeks. The average of all mean PPCs was 71.3%. The average mean PPC was 69.2% in lean-focused journals and 76.2% in other peer-reviewed journals. No significant development trends or patterns were observed in PPC values over time. Figures 3 and 4 show the mean PPC values of articles published in lean construction journals and other peer-reviewed journals, respectively. In these figures, the larger solid black dot indicates the mean PPC of each study, and the smaller dots indicate other measurement results such as the distribution of PPC in each study. Studies showing only a solid black dot only contain mean PPC data and lack other metrics. The horizontal axis of the figure shows the studies identified by code number in chronological order.

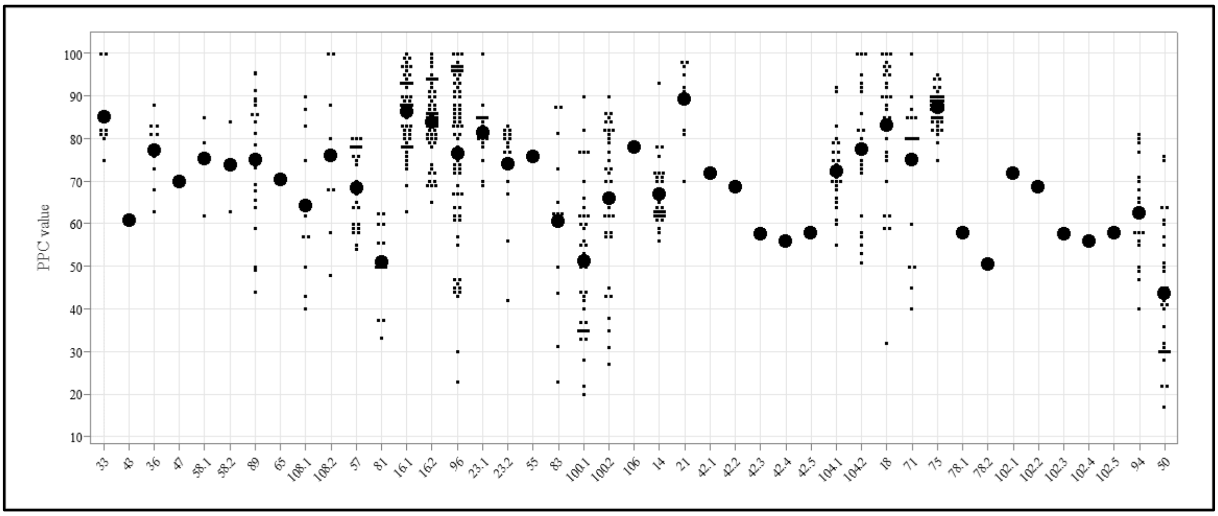

Figure 3: PPC values of articles published in lean construction journals.

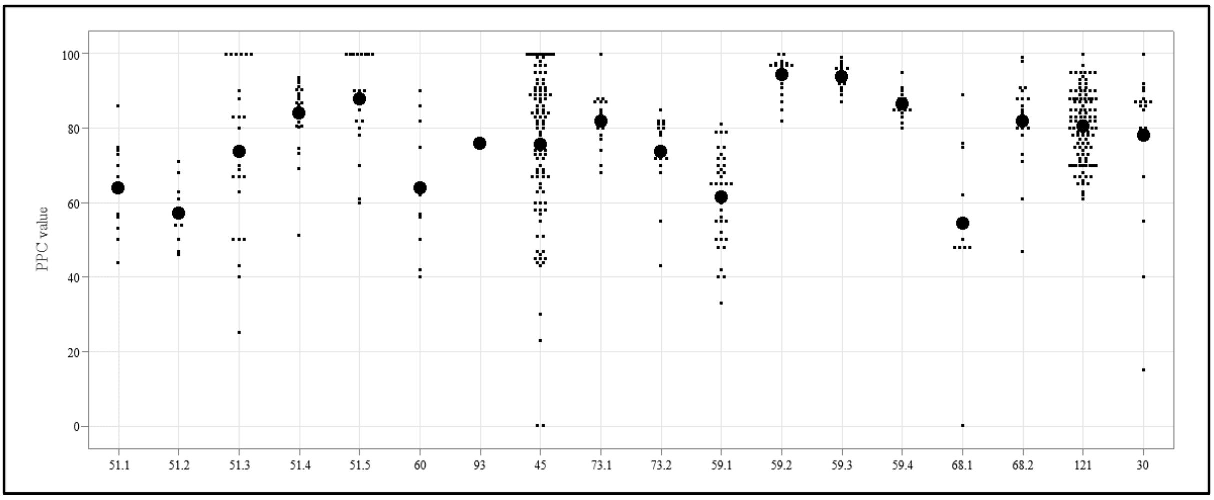

Figure 4: PPC values of articles published in other peer-reviewed journals.

The mean PPC seemingly differed between lean-focused journals and other peer-reviewed journals. Therefore, the researchers first verified that the PPCs of both groups were normally distributed. The fact that they were meant that they could subsequently analyze these two groups using the analysis of variance (ANOVA) method. The ANOVA revealed a statistically significant difference between the groups. The ANOVA results are shown in Table 2.

Table 2: ANOVA results.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	1	618.7	618.7	4.79	0.033 < 0.05
Error	59	7627.0	129.3		
Total	60	8245.7			

Factor	N	Mean	StDev	95 % CI
PPC Mean of lean-focused journals	43	69.20	11.16	(65.73; 72.67)
PPC Mean of other peer-reviewed journals	18	76.18	11.86	(70.82; 81.54)

Pooled StDev = 11.3697

Source = source of the variation in the data, DF = degrees of freedom, Adj SS = adjusted sum of squares, Adj MS = adjusted mean sum of squares, N = total number of PPC observations per group, StDev = standard deviation, CI = confidence interval.

One-way ANOVA revealed a statistically significant difference in PPC between the two publication groups, with an F-value of 4.19 and a p-value of 0.033 ($p < 0.05$).

Figure 5 shows the mean PPC values of the research articles by continent. The larger solid black dot indicates the average of the mean PPC of all results for a continent, and the smaller dots indicate the mean PPCs of individual studies.

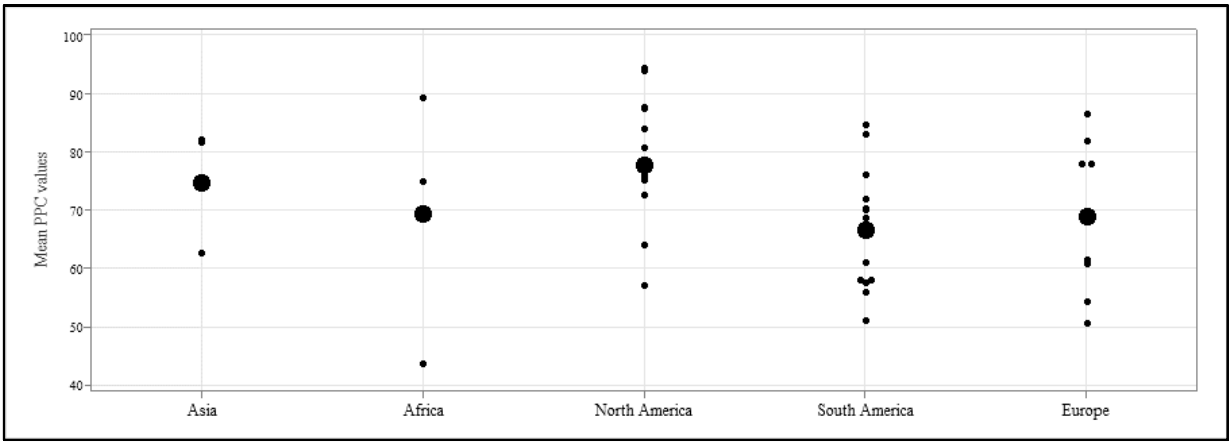

Figure 5: Mean PPC values presented in the reviewed journals by continent.

When compared geographically, the highest mean PPC average was in North America (77.7%, N = 16) and the second-highest one was in Asia (74.9%, N = 7). Europe (69.0%, N = 8) and Africa (69.4%, N = 3) were almost at the same level, and South America (66.7%, N = 14) had the lowest value. Most studies presenting PPC values were in North and South America, followed by Europe, Asia, and Africa.

DISCUSSION AND CONCLUSIONS

With the PPC value constantly at or below 50% on average, the foreman's job is essentially a roll of the dice (Ballard & Tommelein, 2016). Our findings from a large sample of studies in which PPC values have been presented show that the published PPC values are approximately 71% (±5%), although they differ by case and continent. This finding agrees with the findings by Aslam *et al*. (2020) of a mean PPC of 68% (N = 16). Further, no developing (or declining) trend was observed in the data, even though the studies were analyzed between 1998 and 2021. Howell and Macomber (2002) argued that a PPC value of 80% is "good" and one less than 60% is "poor," and very mature teams can maintain a daily PPC of 85%. These findings suggest that the case studies in which the PPC value is close to the "good" level are published in peer-reviewed journals, and a wider range of cases, including some in which the PPC value is "poor," are published in lean-focused journals. At the same time, among case studies presenting PPC that were published in other peer-reviewed journals, only three had PPCs that remained above the 80% level throughout the monitoring period. By contrast, none of the studies published in lean-focused journals had PPCs that maintained this "mature" level of 80% throughout the monitoring period. This might indicate that the PPC level of 80% is too high to be consistently reached and maintained or that construction planning still lacks an understanding of feasibility and that the promises made during LPS meetings continue to ignore and stress all the barriers that might impact task execution. From a learning and development perspective, future research should focus on starting levels of PPC from the cases and evaluate the PPC changes during the studies.

Another study finding was the statistically significant difference between the results of articles published in lean-focused journals and those published in other peer-reviewed articles. The fact that research results showing higher PPC values are published in non-lean focused journals may indicate a publication bias (Thornton & Lee, 2000). These findings raise the questions of whether articles presenting low PPC values remain unpublished in peer-reviewed journals and if so, the effect it has on LPS-related research. However, the findings indicates that studies with lower PPC values are compiled in lean-focused journals and conference publications, possibly indicating that the publishers are trying to prevent publication bias. The findings also raise the questions of whether journals focusing on lean will not publish even lower PPC values or whether the lowest samples of PPC values will be published. This finding requires further qualitative research, because the PPC value itself is not necessarily relevant in the published research. What has been studied is how the results have been interpreted based on PPC and what conclusions have been drawn.

The third finding is the geographical differences in published PPC values, which raises several interesting questions for further research. First, are the geographical differences in PPC due to the more extensive and long-term use of LPS, different ways of applying LPS, or different cultures and societies in the continents? For example, cultural differences can affect how low values can be presented in different cultures. There is evidence of differences in the use of LPS; however, the connection to variations in PPC has not yet been investigated (Power *et al*., 2021). Similarly, in relation to takt production, researchers have observed three different geographically distributed schools in the implementation of the method (Lehtovaara *et al*., 2021); this observation may indicate similarities in the use of LPS as well. Further research into the questions arising from these observations is recommended.

The research is limited by the heterogeneity of the material and the variation in the quality of images and tables. Consequently, the researchers had to perform visual evaluations and manual work, especially on the figures; this could affect the accuracy of the individual PPC values. However, no significant loss in reliability occurred because articles with low-quality figures and tables were excluded. Another limitation is the that the majority of the research data contained individual studies that had combined databases containing several projects, implying that they were an "average of averages" and not individual measurement periods. The third limitation is the meta-nature of the study, in which values are averaged; therefore, the reader should exercise care when interpreting the findings. Averages always conceal variations and other valuable information that may exist in the individual studies considered in this study, and the authors recommend familiarizing oneself with not only the results of these studies but also the original research articles. The fourth limitation is that PPC values can vary depending on the type of project, tasks included in the weekly plan, project constraints, uncertainties and risks, and several other variables that make a project a unique achievement. PPC evaluation is flawed if these variables are not considered, and further research should also assess the impact of these variables and how they appear in different academic publications. In further research on PPC, it is essential to expand toward qualitative methods that will provide deeper insights into the statistics and phenomena.

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ENHANCING EARNED VALUE ANALYSIS WITH INTRINSIC SCHEDULE PERFORMANCE METRICS

Frédéric Bosché[1] and Kat Larabi-Tchalaia[2]

ABSTRACT

The Earned Value Analysis (EVA) is a well-known, widely taught and used project monitoring method in both public and private sectors. It nonetheless has some limitations that have led to the emergence of complementary methods like the Earned Schedule (ES) or the Earned Duration Method (EDM). In this paper, another method is proposed that aims to address the limitations of EVA in terms of schedule performance assessment. This method introduces intrinsic schedule performance metrics that (1) ensure that the schedule performance of the overall project and that of individual work packages (WPs) can be measured reliably and independently from the performance of preceding WPs; and (2) do not converge to neutral values at the end of the project or WP (e.g. schedule variance converging to zero). This means that not only are project managers provided with reliable data throughout the entire project, but it also allows to record the real schedule performance of past projects for benchmarking and future planning. The proposed metrics and their application are demonstrated using simulations illustrating their benefits, or complementarity with current EVA metrics.

KEYWORDS

Earned value analysis, project, schedule, performance, monitoring.

INTRODUCTION

Earned Value Management (EVM) is one of the most long-lasting project management methods to this day. Detailed in the international standard ISO 21508:2018 (ISO, 2018), it is now well-known and used in both public and private sectors. Countries like the USA, Australia, Canada, Japan, the UK and Sweden now use the method extensively and participate in the progression of EVM in the field through the International Performance Management Council (De Marco & Narbaev, 2013).

The Earned Value Analysis is the quantitative technique used as part of EVM to evaluate project performance in terms of time and cost. One of the selling points of EVA is that it calculates metrics that measure cost and time performance independently from one another. However, some limitations of the EVA have also long been highlighted. In particular, the EVA's Schedule Performance Index (SPI) and Schedule Variance (SV) metrics are known to lose interpretative meaning once two thirds of a work package (WP) (or project) is completed (Corovic, 2006), at which point they converge to "perfect" schedule performance (i.e. SPI=1.0 and SV=0.0).

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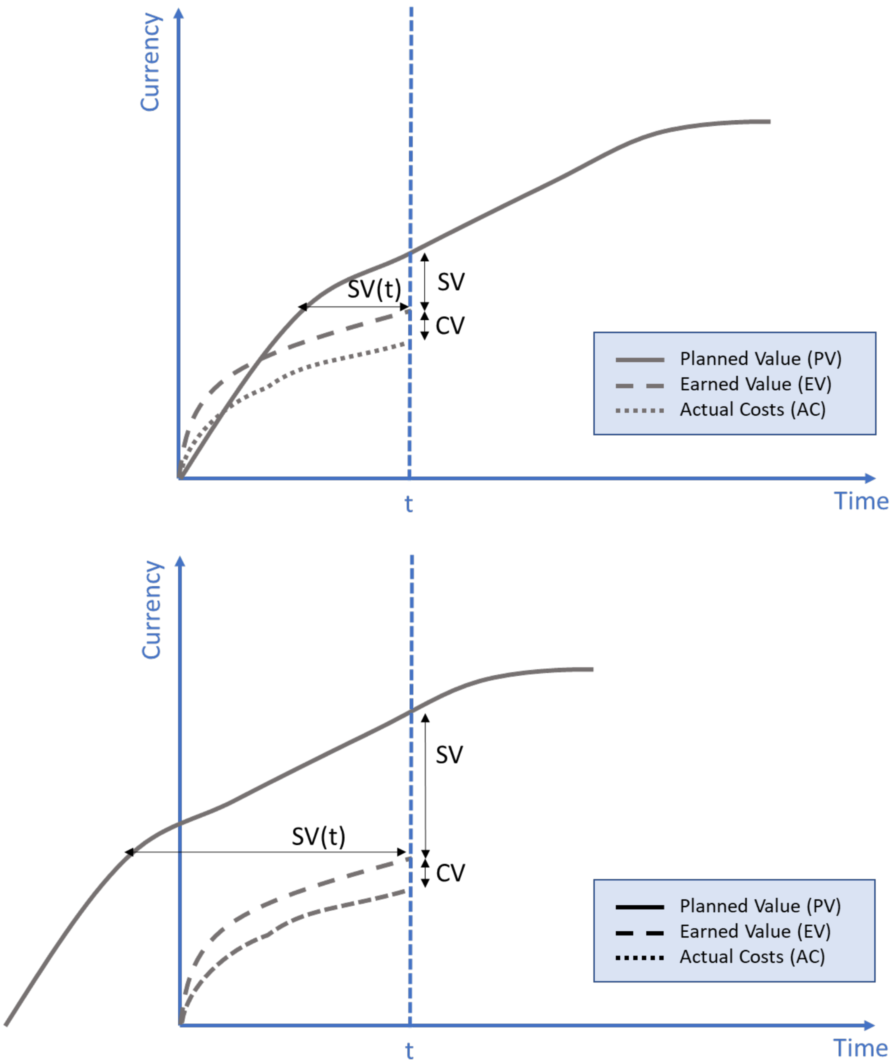
The Earned Schedule (ES) method has been developed by Walt Lipke in the USA and Kym Henderson in Australia (Lipke, 2003; APM, 2013) in order to express the schedule performance in units of time instead of cost (EVA expresses schedule in units of cost), and to address the convergence of the EVA SV and SPI metrics. Its simplicity and compatibility with the existing EVA technique have led to its widespread adoption and it is presented in ISO 21508:2018 (ISO, 2018). Figure 1 (a) shows a typical diagram used to illustrate the EVA and ES methods and how their metrics are calculated on the graph. The formulas for calculating their corresponding performance metrics are summarised in Table 1 (Lipke, 2003; ISO, 2018).

More recently, the Earned Duration Management (EDM) method was proposed by Khamooshi and Golafshani (2014) as a third alternative that distinguishes micro and macro level performance assessment and computes performance (and forecasts) with more direct relation to schedule-related information. Further extensions to EVM and EDM have also been published recently that focus on introducing new fine-tuned metrics (e.g. (Ballesteros-Pérez et al., 2019)), introducing stochastic measures (e.g. (Zohoori et al., 2019; Hendiani et al., 2020)) and improving the forecasting methods (e.g. (Vandevoorde and Vanhoucke, 2006; André de Andrada et al., 2019)).



(a)

(b)

Figure 1: (a) Illustration of the EVA metrics (SV and CV) and the ES metric SV(t): (a) when the actual start date equals the planned start date; and (b) when the actual start date is delayed.

Table 1: Formulas for the calculation of the main performance metrics calculated in the EVA and ES techniques. In this table, AC is the Actual Cost and PV is the Planned Value.

Technique	Metric Name	Metric Acronym	Formula
EVA	Cost Variance	CV	CV = EV - AC
	Cost Performance Index	CPI	CPI = EV / AC
	Schedule Variance	SV	SV = EV - PV
	Schedule Performance Index	SPI	SPI = EV / PV
ES	Schedule Variance [time]	SV(t)	SV(t) = t' - t with t' the time at which PV(t') = EV(t)
	Schedule Performance Index [time]	SPI(t)	SPI(t) = t' / t

Despite the improvements provided by the ES method, some challenges remain. First of all, it must be highlighted that the EVA method does not require the cumulative PV curve to calculate any of its metrics. These are only calculated based on PV, EV and AC values at the performance measurement time t. In contrast, the calculation of EV(t) requires computing the time t' when PV(t') = EV(t). Besides, this requires the PV and EV curves to be aligned to start on the same date. If that is not the case, then SV(t) loses meaning, as shown in Figure 1 (b). It is interesting to note that this requirement is rarely explicitly stated, even in the ISO standard. This is likely because project managers will typically assess schedule performance at the overall project level, at which the start dates of the EV and PV curves will naturally match. However, this is not necessarily true for the Work Packages (WPs) making up the project, due to precedence relationships which can cause the delay in one WP to generate delays in following WPs. In such situations, any following WP will show poor schedule performance from the start, even if they are delivered as planned. These observations also apply to the EDM method.

This paper attempts to provide a solution to the following research problem: can the EVA technique be refined, or extended, to give schedule performance metrics that remain meaningful throughout the delivery of a WP (and the overall project) and do not require the processing of cumulative data for their calculation?

The next section "Method" presents the proposed intrinsic Schedule Performance metrics, with full details on their calculations. The benefits of these new metrics in comparison to existing EVA metrics, and the ES method, are illustrated in the section "Demonstration" with an example, that is kept as simple as possible but perfectly highlights the weaknesses of existing EVA schedule performance metrics (and ES method) and benefits of the proposed new ones. Finally, the section "Conclusion" summarises the results obtained and discusses future works.

METHOD

INTRINSIC SCHEDULE PERFORMANCE

The comparison between Figure 1 (a) and Figure 1 (b) shows how the start date of a WP does not affect the cost performance metric CV (and similarly CPI). In other words, the cost performance metrics (CV and CPI) rightly capture the *intrinsic* cost performance of the WP. In contrast, the figures also show that the start date does have an impact on the schedule performance metrics SV and SPI. In fact, even if a WP is delivered as planned in terms of intrinsic schedule performance, if its start is delayed, then its schedule performance metric SV is negative (and CPI < 1.0) from the outset and for its entire duration up until its completion (due to SV systematically converging to SV = 0.0). This shows that SV and SPI, as calculated in the EVA method, do not capture the *intrinsic* schedule performance of the WP – and should thus be interpreted with great care. It is important to note that these observations also apply to the ES and EDM methods.

In order to determine the *intrinsic schedule performance* of a WP, the PV curve must be (re-)aligned with the EV curve, by setting the planned start date to be the same as the actual start date of the WP. In other words, a separate, *intrinsic* schedule performance baseline (*intPV*) needs to be created for each WP in the WBS and that is set to start on the WP's actual start date. This second baseline, illustrated in Figure 2, is in effect *intrinsic* to the WP, because not impacted by the performance of preceding WPs. Note that an intPV curve needs to be created for each WP at each level in the WBS.

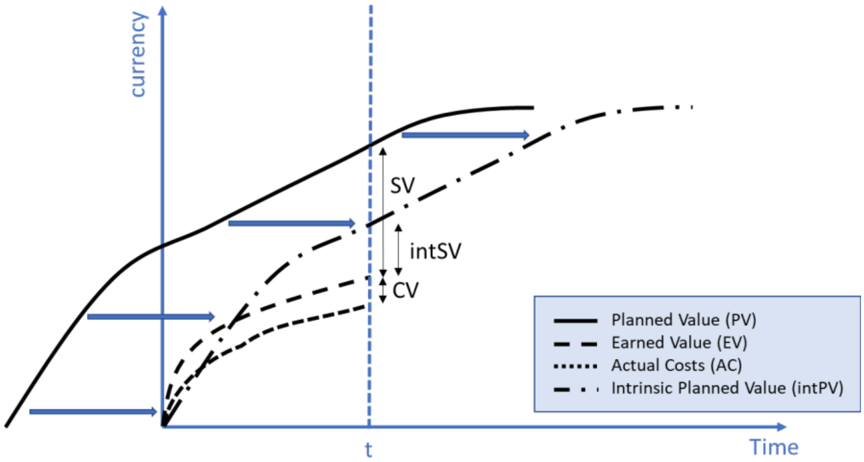


Figure 2: Illustration of the EVA and ES metrics when the intPV curve is added that is the result of (re-)aligning the PV curve with the EV curve (and AC curve).

If PV(t) is the original planned schedule performance baseline of a WP, then the intrinsic baseline intPV(t) can be obtained using the formula:

$$\begin{aligned} intPV(t) &= PV(t-d) \\ &= P\%C(t-d) \times BCWS \end{aligned}$$

where BCWS is the *Budgeted Cost of Work Scheduled*, $P\%C(t-d)$ is percentage of work complete at time (t – d), and:

$$d = S^{actual} - S^{planned}$$

is the difference between the original planned start date $S^{planned}$ and the actual state date S^{actual} of the WP (d is negative if the WP starts earlier than planned).

For completeness, we define *intP%C(t)*, the *intrinsic planned percentage complete* curve calculated as:

$$intP\%C(t) = P\%C(t-d)$$

The formula for intPV(t) then becomes:

$$intPV(t) = intP\%C(t) \times BCWS$$

intPV can now be used to calculate *intrinsic schedule performance metrics*, *intSV* and *intSPI* as:

$$
\begin{aligned}
intSV &= EV - intPV \\
&= (A\%C - intP\%C) \times BAC
\end{aligned}
$$

$$
\begin{aligned}
intSPI &= \frac{EV}{intPV} \\
&= \frac{A\%C}{intP\%C}
\end{aligned}
$$

where $A\%C$ is the *actual percentage of work complete*.

We note that the creation of an intrinsic baseline PV curve, intPV(t), may already be implemented by some practitioners, but such practice is not explicitly suggested in existing standards and most guidance documents, in relation to the ES or EDM methods.

Schedule Performance Convergence Behaviour

While intPV, as introduced above, factors out the impact of the schedule performance of preceding activities on the schedule performance of the activity of interest, intSV and intSPI still converge to 0.0 and 1.0 respectively. This behaviour is illustrated in Figure 3 with the same example where a WP takes longer to complete than planned. The bottom chart shows the evolution of the intSV value as the WP was being completed. The purple part shows the intSV conversion to 0.0, which in that case occurs once the planned duration is passed. Note that the same behaviour occurs if the WP is completed faster than planned. The only difference is that the role of the intPV and EV curves is inverted, i.e. the conversion occurs from when the WP is actually completed until its planned completion date.

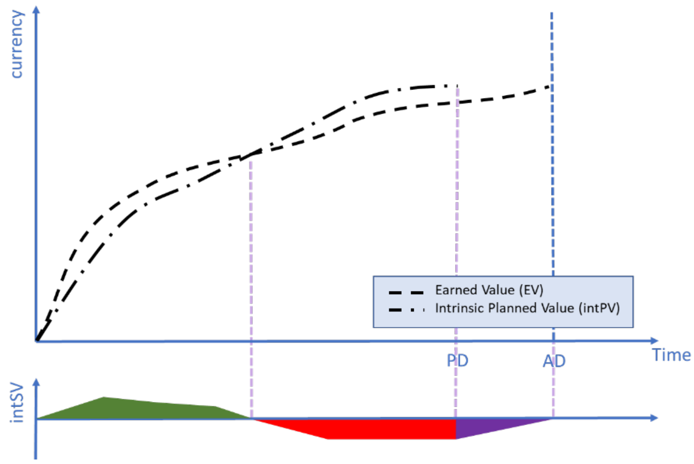


Figure 3: EVA graph for a WP concluding later than intrinsically planned. PD and AD are the planned and actual durations of the WP. The bottom plot shows the evolution of intSV.

To address this limitation, let's start with the case illustrated in Figure 3, of a WP concluding later than planned. In that case, to prevent the conversion, the intPV curve must be artificially extended. This artificial extension of the $intPV$ curve can follow various principles, depending on what may be considered the "financial impact of the difference in completion duration (e.g. delay)". Three approaches are proposed here (illustrated in Figure 4):

a) intPV continues to increase at the same average rate as planned, i.e. for t > PD:

$$intPV_{proj}(t) = \frac{BAC}{PD} \times t$$

b) intPV continues to increase at a rate that maintains intSV at the same value as it was at the time PD (in other words intSV is maintained constant from PD onwards), i.e. for t > PD:

$$intPV_{proj}(t) = EV(t) + intSV(PD)$$

c) intPV continues to increase at a rate that maintains intSPI at the same value as it was at the time PD (in other words intSPI is maintained constant from PD onwards), i.e. for t > PD:

$$intPV_{proj}(t) = EV(t)/intSPI(PD)$$

Note that these options, in particular (b) and (c), follow similar ideas as those proposed for calculating the *Independent Estimate at Completion (IEAC(t))*, i.e. forecasted duration at completion based on various metrics of past performance and assumptions for future performance, in the context of the EVA method (ISO, 2018), the ES method, or the EDM method (Corovic, 2006; Vandevoorde and Vanhoucke, 2006; Jacob and Kane, 2004).

intSV and intSPI are then calculated as normal, i.e. for t > PD:

$$intSV(t) = EV(t) - intPV_{proj}(t)$$

$$intSPI(t) = \frac{EV(t)}{intPV_{proj}(t)}$$

The second case is when a WP is completed earlier than planned. This is illustrated in Figure 5. To prevent the conversion in this case and maintain meaningful intSV and intSPI values, to prevent the conversion of intSV to 0.0 and intSPI to 1.0, intSV and intSPI should simply maintain their values obtained at t = AD, i.e. for t > AD:

$$intSV(t) = intSV(AD)$$

$$intSPI(t) = intSPI(AD)$$

In summary, the proposed strategy to prevent the conversion of intSV and intSPI to 0.0 and 1.0 respectively, is in effect to accrue intPV up to t = AD. In the case of a WP completing earlier than planned, accrual of intPV is simply stopped after t= AD; and in the case of a WP completing later than planned, intPV is accrued artificially after t=PD, until t= AD.

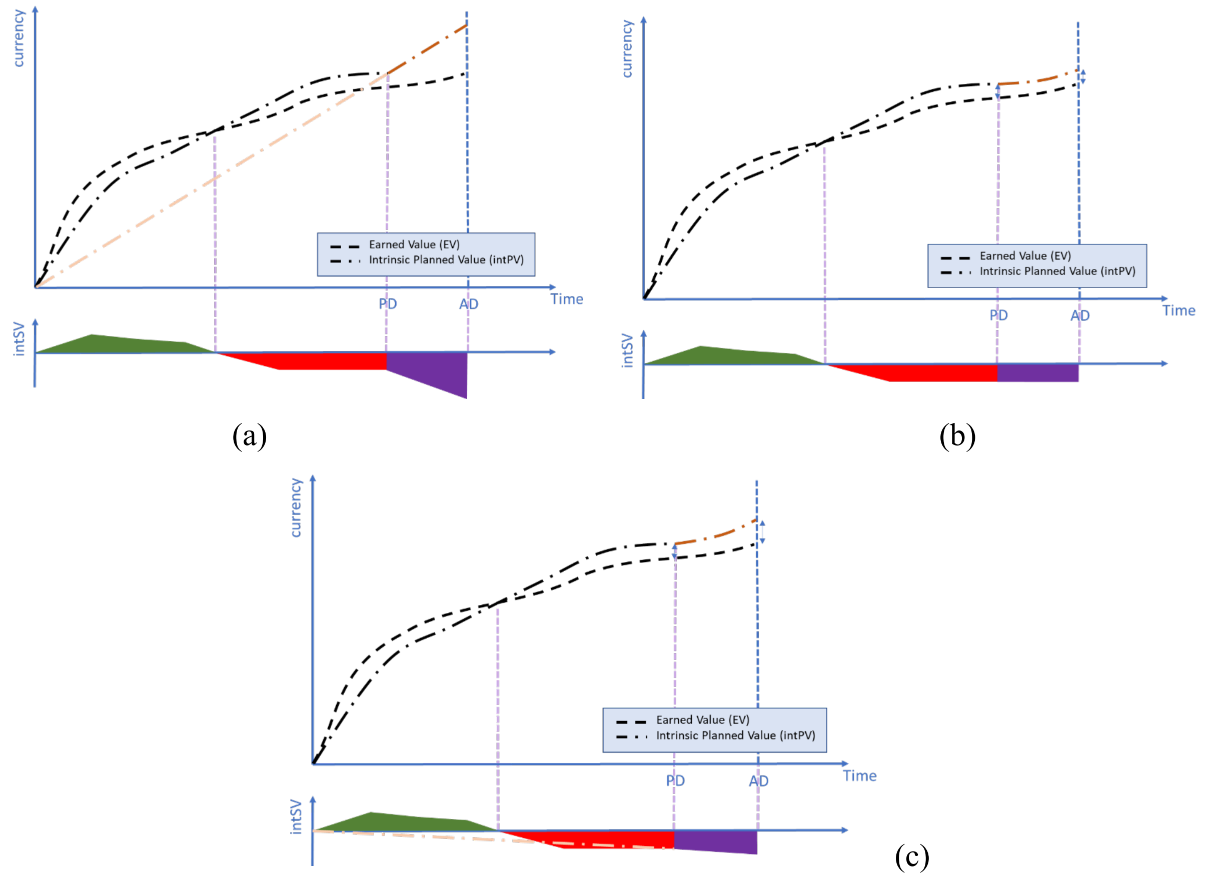


Figure 4: The same EVA graph as in Figure , but where the intPV curve is extended from the PD to AD following three alternative strategies: (a) intPV increases at the same rate as planned; (b) intPV continues to increase at a rate that maintains intSV constant; and (c) intPV increases at a rate that maintains intSPI constant.

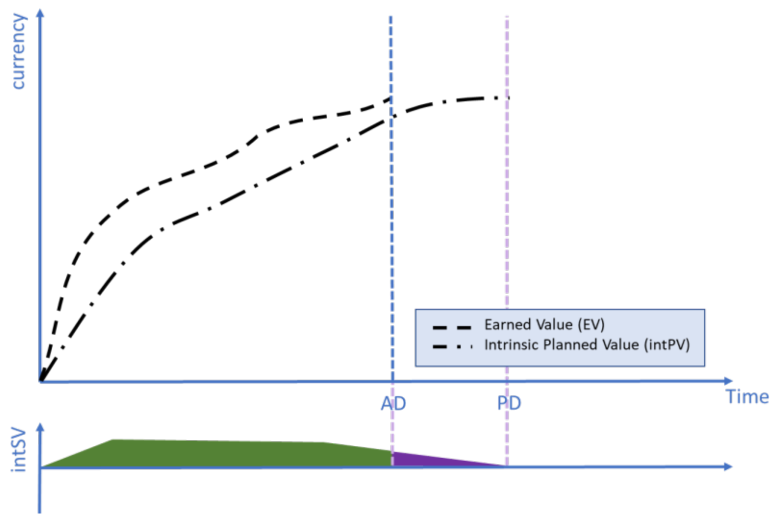


Figure 5: EVA graphs for a WP concluding earlier than planned. PD and AD are the planned and actual durations of the WP, respectively. The bottom plot shows the evolution of the intSV value as the WP was being completed.

SUMMARY

In summary, the proposed method to calculate schedule performance metrics that are intrinsic to the WP (i.e. not influenced by the schedule performance of preceding activities) and that do not converge to 0.0 (SV) and 1.0 (SPI) entails the calculation of: (1) a new curve intPV intrinsic to that WP, no matter its level in the WBS; and then (2) the proposed intrinsic schedule performance metrics intSV or intSPI.

First, the curve intPV is simply a re-baselining of the PV curve so that the planned start date equates the actual start date. Then, intSV and intSPI are calculated as follows:

$$intSV(t) = \begin{cases} EV(t) - intPV(t), & \text{if } t \leq PD \text{ and } t \leq AD \quad \text{[Case 1]} \\ EV(t) - intPV_{proj}(t), & \text{if } t > PD \text{ and } t < AD \quad \text{[Case 2]} \\ intSV(AD), & \text{if } t \leq PD \text{ and } t > AD \quad \text{[Case 3]} \end{cases}$$

$$intSPI(t) = \begin{cases} \frac{EV(t)}{intPV(t)}, & \text{if } t \leq PD \text{ and } t \leq AD \quad \text{[Case 1]} \\ \frac{EV(t)}{intPV_{proj}(t)}, & \text{if } t > PD \text{ and } t < AD \quad \text{[Case 2]} \\ intSPI(AD), & \text{if } t > AD \text{ (including for } t \leq PD) \quad \text{[Case 3]} \end{cases}$$

In the above formulas, the three cases correspond to the following contexts:

d) Case 1: WP is on-going, and its PD and AD are not reached yet.

e) Case 2: WP is on-going, and the PD has been passed (i.e. it is taking longer than planned).

f) Case 3: WP is completed but the PD has not been passed yet (i.e. it took less time than planned).

For Case 2, $intPV_{proj}$ can be calculated using either of the three formulas below depending on the expected schedule performance from the measurement point to completion (other formulas may also be considered):

$$intPV_{proj}(t) = \begin{cases} \frac{BAC}{PD} \times t, & \text{if projection is based on planned performance} \\ EV(t) + intSV(PD), & \text{if projection maintains } intSV \text{ measured at time } PD \\ EV(t) \;/\; intSPI(PD), & \text{if projection maintains } intSPI \text{ measured at time } PD \end{cases}$$

It must be highlighted that the method can be applied for any WP in the WBS, which includes the project overall as well.

DEMONSTRATION

To illustrate the method, Figure 6 shows a simple sequence of two WPs (1.a and 1.b) that are part of a WP higher in the WBS (1). In this diagram, the green bars represent the WPs according to the planned schedule, and the red bars represent the WPs according to the actual schedule. The green bars with the hash represent the WPs according to the intrinsic planned schedule, i.e. planned schedule baseline shifted so that the planned start date is aligned with the actual start date and (artificially) extended up until AD, if needed. We assume that the start of the overall WP was delayed due to some preceding WP having been completed late.

The intrinsic schedule performance metrics and current EVA schedule performance metrics for the two WPs and the overall WP at the end of days 2, 4, 6 and 8 are summarised in Table 2. For simplicity, but without loss of generality, all schedule performance metrics are calculated with the assumption that the PV, intPV and EV progress linearly through the WP durations. In this example, intPV is projected beyond PD using the second projection option defined above, i.e. by assuming that the intSV will remain constant until completion.

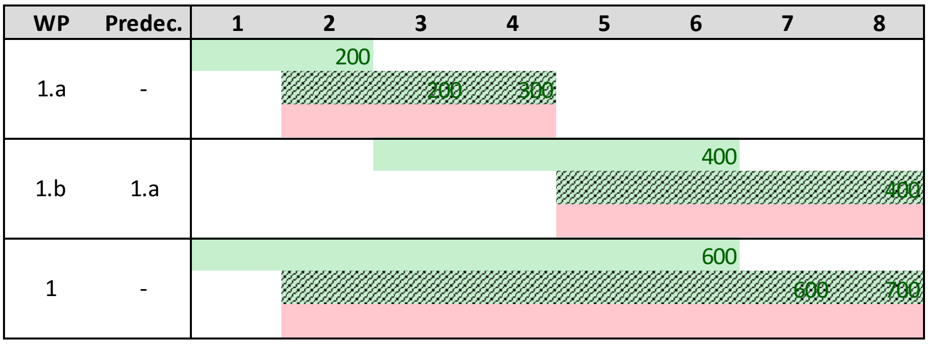


Figure 6: Gantt chart of two sequential WPs. In green: planned delivery. In red: actual delivery. In green with hash: intrinsic planned (i.e. planned baseline aligned to actual start). The numbers indicate the costs (planned and actual) of each WP.

Table 2: The intrinsic schedule performance KPIs and current EVA schedule performance KPI for the two WPs and the overall WP at the end of days 2, 4, 6 and 8.

Day	WP	intSV	intSPI	SV	SPI	intPV	PV	EV
2	1.a	-33	0.67	-133	0.33	100	200	67
	1.b	0	n/a	0	n/a	0	0	0
	1	-33	0.67	-133	0.33	100	200	67
4	1.a	-100	0.67	0	1.00	300	200	200
	1.b	0	n/a	-200	0.00	0	200	0
	1	-100	0.67	-200	0.50	300	400	200
6	1.a	-100	0.67	0	1.00	300	200	200
	1.b	0	1.00	-200	0.50	200	400	200
	1	-100	0.80	-200	0.67	500	600	400
8	1.a	-100	0.67	0	1.00	300	200	200
	1.b	0	1.00	0	1.00	400	400	400
	1	-100	0.86	0	1.00	700	600	600

The intrinsic performance metrics correctly reflect the fact that WP 1.a took 50% more time than planned and that, schedule-wise, WP 1.b is intrinsically performing as planned. In contrast, the SPI and SV values as defined in the EVA technique suggest a completely different picture with 1.a overestimating the delay at day 2 and then converging to 1.0 at day 4 when the activity is actually completed. Similarly, for WP 1.b, SV reports that the activity is behind schedule, but this is only due to the delay of WP 1.a, and not intrinsically due to WP 1.b itself. Then, at day 4, SV and SPI continue to suggest the activity is behind schedule, while it is in fact intrinsically proceeding as planned. And, again, at day 8 the SV and SPI converge to 1.0, thereby losing interpretation meaning. Looking at the overall WP 1, the SPI values suggest at day 2 that the WP is significantly behind schedule (0.33) and then delays are recovered throughout the completion of the WP until the SPI value converges to 1.0 at the end. But, in reality, WP1 does get behind schedule at the beginning due to WP 1.a, but later maintains performance with WP 1.b. This is rightly captured by intSPI that gives a 0.67 value up to day 4, and then 0.8 and 0.86 at days 6 and 8 respectively. The final value is logical since it ultimately took 7 days to deliver the WP which was initially planned for 6 days (6 / 7 = 0.86).

Because the proposed intrinsic schedule performance metrics do not systematically converge to 0.0 (SV) or 1.0 (SPI), they retain intrinsic performance which enables project management teams to more easily trace back the origins of performance deviations. These would also be very useful for organisations to store historical records of the schedule performance of common types of works, which could then be used for benchmarking and enhance the quality of planning for future projects.

In addition, as indicated earlier, because WP 1 starts later than planned, the ES metric SV(t), if calculated with the PV curve as opposed to the intPV curve, is negative from Day 1 and increases subsequently. While it would correctly capture the delay of WP 1 in the context of the broader project (SV(t) = - 2 days at t=8), this would not correspond to the intrinsic schedule performance of the WP that has a delay of only 1 day.

CONCLUSION

In this paper a new set of schedule performance metrics are proposed to complement and strengthen the existing EVA technique. The benefits of the method are that:

- It captures the intrinsic schedule performance of any WP at any level of the project WBS (including the overall project) independently from the performance of preceding activities.
- It ensures that intSPI does not systematically converge to 1, and similarly intSV does not systematically converge to 0. Instead, both continuously and correctly measure the intrinsic schedule performance throughout the duration of WP. This property is useful (1) for project management teams to be able to trace back the source of any performance deviation; and (2) for organisations to keep historical records of past schedule performance to support the planning and monitoring for future projects (e.g. a certain type of work might be more likely to cause delays).
- It does not require any additional input from that needed for the traditional EVA. It can thus easily be added to existing software solutions.
- It provides schedule performance metrics without needing to conduct any look up in the PV curve, as needed by the ES and EDM methods. But, in contrast to those methods, it reports schedule performance in units of cost as opposed to units of time. With regard to the ES and EDM methods, this paper also shows how, although never explicitly discussed in the literature, they should be applied with the intPV curve, not the PV curve.

While the experimental results positively illustrate these benefits, further validation will naturally be pursued with more complex data – ideally from real projects – in order to identify potential challenges or barriers to implementation in practice. Besides, more formal and detailed comparisons of the proposed approach with the ES and EDM methods should be conducted.

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ASSESSMENT OF LEAN GUIDED CONSTRUCTION PROJECT MONITORING AND EVALUATION PRACTICES: ISSUES AND CHALLENGES

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ABSTRACT

Monitoring and evaluation (M&E) practices in construction projects are valuable for managing the execution and ensuring quality project delivery. However, implementing the lean-guided M&E practice in construction projects faces different issues and challenges. The study considered issues and challenges in lean-guided monitoring and evaluation practices for construction projects in South Africa. A field survey was carried out among construction professionals in Mpumalanga province, South Africa, to identify issues and challenges they faced in lean-guided M&E practices on construction project activities. A random sampling method was used to collect data, and 36 questionnaires were retrieved from the construction professionals within the study area. Data collected were computed using a descriptive statistical approach. The valid mean item score was determined in this study by utilizing a statistical data equation (mathematical equation). The study's findings showed that lack of dedicated management staff, proper documentation, and construction project goals were the highest-ranked challenges facing lean-guided M&E practices in construction projects. The study concluded that construction professionals should be trained on lean principles and their application in different aspects of construction management and planning to improve the M&E practices on construction sites to achieve set project goals.

KEYWORDS

Construction Projects, constraint analysis Evaluation, Time compression, standardization, South Africa.

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INTRODUCTION

The procedure for controlling and examining the construction project process to ensure that professionals involved meet the project objectives is M&E (Ogunbayo et al., 2022). Tengan and Aigbavboa (2019) state that M&E is a tool that aids effective project performance. It is also a valuable tool for managing the execution and successful project delivery (Kissi et al., 2019; Ogunbayo & Aigbavboa, 2019).

M&E is a project management function aimed at sequentially collecting information on construction projects to inform stakeholders involved on the progress on cost, quality, and time triangle towards promoting organizational learning and management decision (Otieno, 2000; Tengan and Aigbavboa 2016; Kusek and Rist 2004). However, M&E, aided by the lean principle for construction projects, will define a clear set of objectives for the delivery process of construction projects. Effective use of the Lean construction principle in guiding the M&E system in construction projects will improve production control throughout the project's life (Locatelli et al., 2013).

Construction professionals and other stakeholders benefit from effective M&E by avoiding unforeseeable issues (Ogolla & Moronge, 2016; Ogunbayo & Mhlanga,2021). In project appraisal for construction work, M&E needs to be complete and ready for projects to be sustainable and relevant (Muiga, 2015). M&E practices in construction projects make it simpler for the construction professional to execute the construction program for an effective production process. Tengan and Aigbavboa (2016) postulated that M&E practices in construction projects are management functions for effective project resource organisation. Hence, M&E is significant to construction industry performance by facilitating strategic decision-making for successful project implementation (Otieno,2000). Nonetheless, Thomas et al. (2003) noted that the main effort of lean thinking in M&E practice in a project is to reduce the high variability that affects it through a more reliable workflow of information, materials, and equipment carried out mainly through the last planner system. Further, Howell et al. (2004) sustain that lean construction and principle is not only about project activity optimization by activity but overall project optimization with bases for consideration on how every single activity affects the next.

Despite efforts made by construction professionals to achieve lean-guided M&E practice in the construction industry, the process faced different issues and challenges. Also, fewer studies have established the issues and challenges affecting lean-guided M&E practices within the construction industry, especially in developing economies (Ogolla & Moronge, 2016; Tengan & Aigbavboa, 2019). Hence, this study uses the South African construction industry as a case study to assess issues and challenges in lean-guided M&E practices in construction projects.

LITERATURE REVIEW

Developing economies' inability to deliver construction projects successfully is based on poor implementation of M&E and practice (Otieno, 2000; Ogunbayo et al., 2018). Construction projects in these countries faced different issues and challenges hindering the lean-guided M&E practice within their construction industry (Bohn & Teizer, 2010). These issues and challenges affected developing economies' construction industry, including South Africa, in meeting their construction target leading to abandonment and delays in construction delivery (Tengan &Aigbavboa, 2016; Ogunbayo et al., 2021).

Bhagavan (2004) states that in the construction industry of developing economies, lean-guided M&E practices are affected by weak government policies, political conflict, corruption among policymakers (government), and a lack of standard M&E guidelines. Similarly, weak government institutions have made the M&E practice in the construction industry face issues and challenges (Oloo, 2011). This has caused corruption among stakeholders (government and construction professionals) involved in the tendering process for construction projects and impacts the lean-guided M&E practice and its implementation (Crawford & Bryce, 2003).

Chaplowe and Cousins (2015) state that lean-guided M&E practice needs a combined effect of good planning, budgeting, and construction targets to achieve all stages in the construction project cycle. However, Prennushi, Rubio, and Subbarao (2002) assert that the lack of construction project goals, objectives, and standard guides or planning for the construction industry are issues and challenges affecting the lean-guided M&E practice in developing economies. Waithera and Wanyoike (2015) noted that insufficient data gathering, poor construction methodology, and construction documentation were issues and challenges affecting lean-guided M&E practice in construction operations and processes. This clearly shows that the weak link between construction project goals, objectives, standard guides or planning, and M&E practice will lead to issues and challenges affecting construction activities (Prennushi et al., 2002; Ogunbayo et al., 2021).

Badom (2016) postulated that in ensuring effective lean-guided M&E practice in construction projects, stakeholders must be dedicated to its implementation, especially by working with appropriate construction documents and lean principles. Zhou and Hardlife (2013) assert that this process can be difficult due largely to a lack of a dedicated management team, poor construction documentation, and a shortage of skilled construction professionals. Similarly, Tengan and Aigbavboa (2016) noted that lean-guided M&E practice is a process that can improve construction proceedings, but its implementation within the construction industry is hindered by insufficient funding allocation by the government, lack of resources and knowledge on lean principle for M&E implementation for construction projects.

Kusek and Rist (2004) posit that a corrupt-free system within a country has a multiplying impact on national economic development, including the construction industry. However, Masoetsa et al. (2022) postulated that the construction industry's economic expansion problem without adequate planning for bureaucracy to cater for lean-guided M&E practice toward a healthy construction industry has led to issues and challenges affecting project executions. Also, the lean-guided M&E practice faces implementation problems in construction projects due to corruption and unethical behaviour of construction workers on sites (Kamau & Mohamed, 2015).

Further, Issa (2013) reveals that Lean construction techniques and principles can potentially reduce the effects of risk factors (issues and challenges) on cost, quality, and time objectives during the M&E process for construction projects. On this note, studies on the significance of using lean construction in construction projects have been conducted in different countries (Adamu & Hamid, 2012; Akinradewo et al., 2018; Fiallo & Revelo, 2002). Further attempts have been made to apply lean principles and techniques to construction project management processes, including the M&E aspect of the construction projects, production control, design, project delivery system, and supply. Koskela et al. (1996) studied a fast-track office building project, and the study's findings showed how the building process could be made leaner and speedier. The study of Tsao et al. (2000) indicated how lean thinking and work structuring helped improve the construction process's design and installation. The finding of the study by Ballard et al. (2002) illustrated the power of lean concepts and techniques and their applicability to construction project processes and operations.

Table 1: Issues and challenges affecting M&E practices.

s/n	Issues and Challenges	Authors	Countries
1	Lack of dedicated management staff	Kusek and Rist (2004)	USA
		Badom (2016)	Nigeria
2	Lack of proper construction documentation	Prennushi et al. (2002)	USA
		Crawford and Bryce (2003)	Australia
3	Lack of construction project goals	Prennushi et al. (2002)	USA

		Chaplowe and Cousins (2015)	USA
4	Corruption in the construction projects tender process	Crawford & Bryce (2003)	Australia
		Kamau & Mohamed (2015)	Kenya
5	Lack construction objectives	Locatelli et al. (2013)	UK
		Ogolla & Moronge (2016)	Kenya
6	Problem of economic expansion of the construction industry	Kusek and Rist (2004)	USA
		Masoetsa et al. (2022)	South Africa
7	Lack of M&E policy by the government	Oloo (2011)	Kenya
		Bhagavan (2004)	Sweden
8	Corruption among government personnel	Crawford & Bryce (2003)	Australia
		Bhagavan (2004)	Sweden
9	Corruption among construction workers	Bhagavan (2004)	Sweden
		Oloo (2011)	Kenya
10	Lack of standard guide for the construction industry	Crawford and Bryce (2003)	Australia
		Zhou and Hardlife (2013)	Zimbabwe
11	Unethical behaviour of construction workers	Crawford and Bryce (2003)	Australia
		Bhagavan (2004)	Sweden
12	Shortage of skilled M&E team	Zhou and Hardlife (2013)	Zimbabwe
		Tengan and Aigbavboa (2016)	Ghana
13	Lack of knowledge of implementing M&E	Bhagavan (2004)	Sweden
		Oloo (2011)	Kenya
14	Political conflicts	Crawford & Bryce, 2003	Australia
		Chaplowe and Cousins (2015)	USA
15	Lack of construction resources	Kusek and Rist (2004)	USA
		Tengan and Aigbavboa (2016)	Ghana
16	Insufficient data gathering	Kusek and Rist (2004),	USA
		Tengan and Aigbavboa (2019)	Ghana
17	Lack of proper construction methodology	Prennushi et al. (2002)	USA
		Waithera and Wanyoike (2015)	Kenya
18	Insufficient construction funding	Kusek and Rist (2004)	USA
		Tengan and Aigbavboa (2016)	Ghana

However, the application of the lean principles in the M&E process still faces issues and challenges that need to be identified as it affects the construction project processes and operations (Badom, 2016; Kusek & Rist, 2004; Tengan & Aigbavboa, 2016). Additionally, it is critical to identify issues and challenges as it affects the lean-guided M&E practice in construction projects. This is because the political climate around construction projects (on and off the project site) might make it difficult to have effective and efficient lean-guided M&E practices within the project (Masoetsa et al., 2022). These issues and challenges, as highlighted in Table 1, have deprived M & E practitioners within the developing economies' construction industry of meeting the demand for effective construction project flow, budgeting, execution, and delivery (Oloo, 2011; Kamau and Mohamed, 2015; Tengan & Aigbavboa, 2016; Masoetsa et al., 2022). This study aims to affirm these issues and challenges in M&E practice as it affects construction project operations and processes in developing countries using the South African construction industry as a case study.

METHODOLOGY

This study was carried out within Mpumalanga province in South Africa among construction professionals working on construction projects within the construction industry. Respondents for this study were selected based on their involvement and experience with the M&E process in construction projects. Mpumalanga province was chosen for this study because it has many ongoing construction projects (government and private projects) with M&E units established within their construction process. Through the systematic random sampling method, 50 (fifty) questionnaires were administered to the respondents, and 36 (thirty-six) were retrieved. This study used the systematic random sampling method because it is easier and more direct and eliminates the possibility of clustering when adopted than cluster sampling, which breaks the population into different clusters and takes a simple random sample from each cluster. (Rea & Parker, 2014). It also tends to cover all the elements evenly (Ogunbayo et al., 2022). The questionnaire was designed on a 5-point Likert scale and recorded a 72% response rate, using Strongly Disagreeing=1, Disagreeing=2, Neutral=3, Agreeing=4, and Strongly Agree=5.

The respondents were asked questions about their genders, years of experience, profession, and type of construction projects they were involved in the construction industry. Through the questionnaire, respondents were further asked about eighteen issues and challenges facing M&E practices in construction projects identified from the literature. After computation, the issues and challenges identified were sorted from the highest to lowest in terms of their mean item score (MIS). This helped this study assess issues and challenges affecting lean-guided M&E practices in construction projects within the study area. The study adopted descriptive statistical tools using MIS to analyse how participants rated various questions in the survey questionnaire. According to Pallant (2020), means are significant in descriptive research since they reveal average participant scores on a given measure.

RESULTS

Figure 1 reveals the respondents' gender. The result shows that 69.44% (25) of respondents are male, while 30.56% (11) are female construction professionals within the study area.

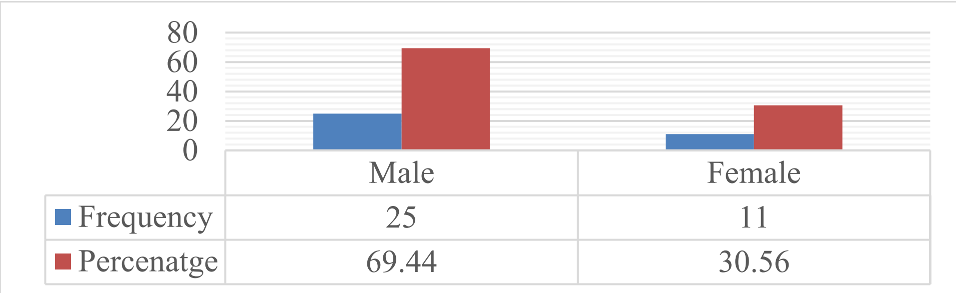

Figure 1: Respondent’s gender

Figure 2 reveals the respondents' years of experience in M&E within the construction industry. The result reveals that 25% (9) of respondents have 0-5years of experience, 41.67% (15) have 6-10 years of experience, 19.44% (7) have 11-15 years of experience, while 13.89% (5) of the respondents have above 16 years of experience.

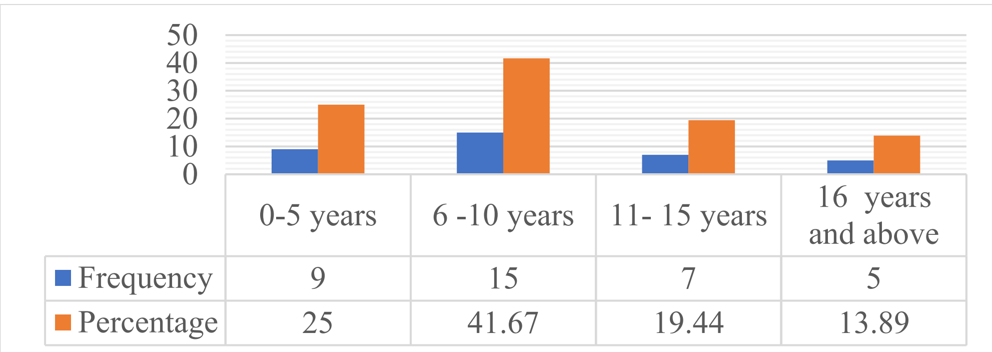

Figure 2: Respondents’ years of experience

Figure 3 shows the respondent's profession in the construction industry. As shown in Figure 3, 22.22% (8) of the respondent are civil engineers,27.78 % (10) of the respondents are construction managers, 19.44% (7) are construction project managers, 25% (9) are quantity surveyors, while 5.56% (2) are other comprises of an architect and a consultant.

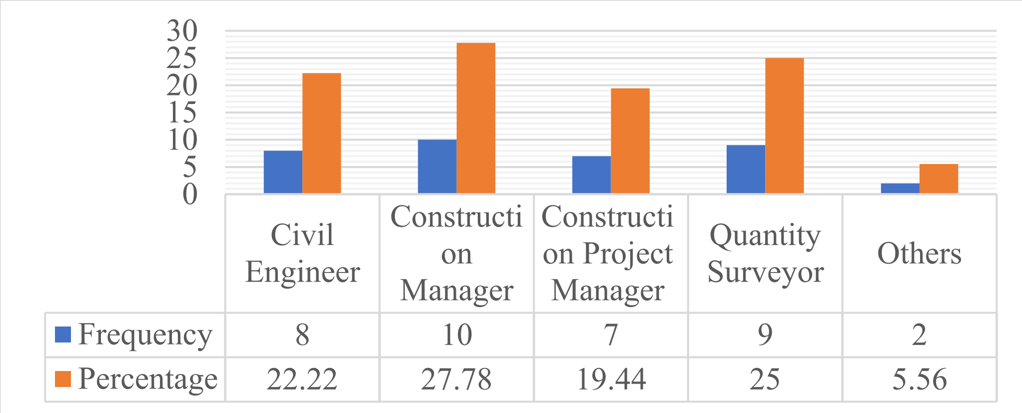

Figure 3: Respondents' professions

Figure 4. reveals the type of construction projects where respondents carried out their M&E practices within the construction industry. The outcomes indicate that 22.22% (8) of the respondents carried out their M&E practices in residential buildings projects, 16.67% (6) of the respondents are involved in civil and road projects,33.33% (12) of the respondents are engaged in private and commercial projects, while 27.78% (10) are involved in government projects within the construction industry.

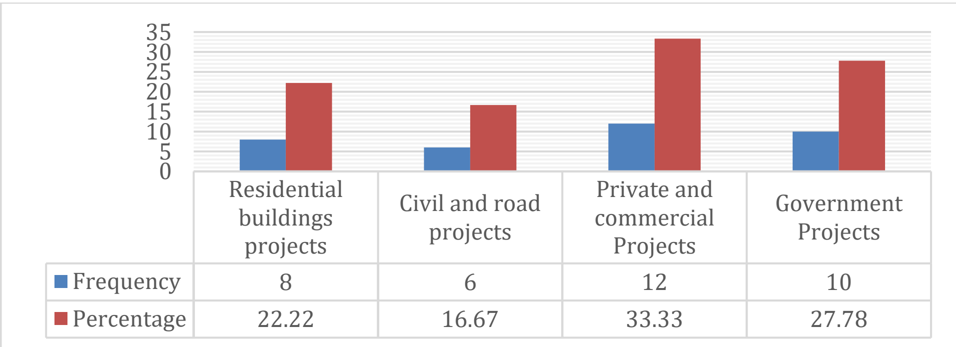

Figure 4: Type of construction projects respondents carried out their M&E practices.

Table 2: Ranking of issues and challenges facing lean-guided M&E practices by respondents

s/n	Issues and Challenges	$\bar{x}$	σX	R
1	Lack of dedicated management staff	4.44	0.773	1
2	Lack of proper construction documentation	4.25	0.937	2
3	Lack of construction project goals	4.19	1.009	3
4	Corruption in construction projects tender process	4.11	0.854	4
5	Lack construction objectives	4.08	0.874	5
6	Problem of economic expansion of the construction industry	4.03	0.774	6
7	Lack of M&E policy by the government	4.00	0.828	7
8	Corruption among government personnel	3.89	1.008	8
9	Corruption among construction workers	3.83	1.000	9
10	Lack of standard guide for the construction industry	3.83	0.845	9
11	Unethical behaviour of construction workers	3.81	0.951	11
12	Shortage of skilled M&E team	3.75	1.317	12
13	Lack of knowledge of implementing M&E	3.75	1.052	12
14	Political conflicts	3.75	0.967	12
15	Lack of construction resources	3.72	1.031	15

16	Insufficient data gathering	3.69	1.238	16
17	Lack of proper construction methodology	3.64	0.990	17
18	Insufficient construction funding	3.61	1.128	18

Mean of the values = $\overline{x}$; Standard Deviation (SD)= σX; Rank = R

Table 2 illustrates the respondent ranking of issues and challenges facing lean-guided M&E practice within South African construction projects. The outcomes show the top and low ranked issues and challenges facing lean guided M&E practice within construction projects delivery and they include; lack of dedicated management staff ranked first with a $\overline{x}$ of 4.44 and a σX of 0.773; ranked second was lack of proper construction documentation with a $\overline{x}$ of 4. 25 and a σX of 0.937; while lack of construction project goals was ranked third with a $\overline{x}$ of 4.19 and a σX of 1.009; corruption in construction projects tender process was ranked fourth with a $\overline{x}$ 4.11 and σX of 0,854; lack of construction objectives was ranked fifth with a $\overline{x}$ of 4.08 and a σX of 0.874; ranked sixth was problem of economic expansion of the construction industry with a $\overline{x}$ of 4.03 and a σX of 0.774; while lack of M&E policy by the government was ranked seventh with a $\overline{x}$ of 4.00 and a σX of 0.828; corruption among government personnel was ranked eighth with a $\overline{x}$ of 3.89 and a σX of 1.008; while corruption among construction workers with a $\overline{x}$ of 3.83 and a σX of 1,000 was ranked ninth; lack of standard guide for the construction industry was also ranked ninth with a $\overline{x}$ of 3.83 and a σX of 0.845. In addition, unethical behaviour of construction workers was ranked eleventh with a $\overline{x}$ of 3.81 and a σX of 0.951; shortage of skilled M&E team was ranked twelfth with a $\overline{x}$ of 3.75 and a σX of 1.317; lack of knowledge of implementing M&E was also ranked twelfth with a $\overline{x}$ of 3,75 and a σX of 1,052; ranked twelfth was political conflicts with a $\overline{x}$ of 3,75 and a σX of 0,967; lack of construction resources was ranked fifteenth with a $\overline{x}$ of 3,72 and a σX of 1,031; while insufficient data gathering was ranked sixteenth with a $\overline{x}$ of 3,69 and a σX of 1,238, ranked seventeenth was lack of proper construction methodology with a $\overline{x}$ of 3,64 and a σX of 0,990; and insufficient construction funding was ranked lastly with a $\overline{x}$ 3,61 and a σX of 1,128.

DISCUSSION OF FINDINGS

The study assessed the issues and challenges in construction project M&E practices in construction project delivery within the South African construction industry. The result of the study indicated that lack of dedicated management staff, lack of proper construction documentation, lack of construction project goals, corruption in the construction project tender process, lack of construction objectives, and the problem of economic expansion of the construction industry were the highest-ranked (1st - 6th) issues and challenges facing lean guided M&E practice. The finding aligns with Prennushi et al. (2002) and Crawford and Bryce (2003) that lack of project goals, corruption in the tender process of projects, and absence of objectives for construction projects were challenges facing lean-guided M&E practices in construction work. Similarly, the finding agrees with Kusek and Rist (2004), Waithera and Wanyoike (2015), Badom (2016), and Masoetsa et al. (2022) that improper construction documentation, economic expansion of the construction industry, and lack of dedicated management staff were issues affecting lean-guided M&E practices in the construction industry. The study's findings imply that poor management processes in contract documents, such as bills of quantity, construction agreements, general conditions, special conditions, and drawings, affect M&E practices for construction projects if not well guided by lean principles.

The findings also showed that lack of M&E policy by the government, corruption among government personnel, corruption among construction workers, lack of standard guide for the construction industry, unethical behaviour of construction workers, shortage of skilled M&E team, lack of knowledge of implementing M&E and political conflicts were mediumly ranked (7th – 12th) issues and challenges facing the M&E practice in the construction industry. The study affirmed Bhagavan (2004), Oloo (2011), and Masoetsa et al. (2022) that issues and challenges facing M&E practices in the construction projects were poor government policy on M&E, corruption among government officials in the M&E documentation process, corruption among construction workers in the production process, absent of M&E specialist, and poor knowledge on the implementation of M&E procedures. This study findings also agree with Crawford and Bryce (2003) and Zhou and Hardlife (2013) that the lack of a standard guide for the construction industry, unethical behaviour of construction workers, and political conflicts and instability were issues and challenges facing M&E practices in construction projects. The study findings imply that M& E of construction projects guided by lean principles will not be effective in the construction projects if issues such as corruption in the construction process and operation are not deterred. This can also lead to substandard work caused by unethical behaviour among construction workers and poor understanding of the lean principle.

Further, the findings indicated that lack of construction resources, insufficient data gathering, lack of proper construction methodology, and insufficient construction funding was the least ranked (15th -18th) issues and challenges facing the M&E practice in construction projects. This supports Kusek and Rist (2004), Waithera and Wanyoike (2015), and Tengan and Aigbavboa (2019) that poor funding of the construction industry, scarce construction resources, inadequate data gathering, and dearth of proper construction methodology were issues and challenges facing the M&E practices in the construction projects. The study findings imply that poor understanding of the lean principles in the M&E practices can lead to poor handling of the construction methods and resources. This might affect the use of digital tools, especially in gathering enough data information for the construction process and operation. Moreover, lack of understanding and usage of the lean construction principle among M&E practitioners in construction projects might discourage clients or project sponsors, especially in mega construction projects, from being conscious of providing projects funding because of the poor establishment of the lean principle on M&E practice for the construction projects.

CONCLUSIONS

The study assessed issues and challenges facing lean-guided M&E practice in construction projects in the South African construction industry. The study identified a lack of dedicated management staff, lack of proper construction documentation, lack of construction project goals, corruption in the construction project tender process, lack of construction objectives, and the problem of economic expansion of the construction industry as major issues and challenges facing M&E practice in construction project delivery. These issues and challenges were caused by the construction professionals' poor understanding of lean construction principles. The study suggested that to avoid issues and challenges in lean-guided M&E practices in construction project delivery, government personnel and construction professionals involved in construction M&E should be trained on lean construction principles and their application to different aspects of construction management planning. The study concluded that construction project M&E practice should be guided by proper government policy enacted through the Act of the parliament. Government agencies such as the Construction Industry Development Board (CIDB) and other construction professional bodies in South Africa and other developing countries should establish monitoring and enforcement units guided by lean construction principles to monitor the implementation of M&E practices on construction projects. The study contributes to the body of knowledge by making the professionals and government agencies involved in construction project delivery identify issues and challenges anticipated in lean-guided M&E practices and the need to understand the importance of lean construction principles toward achieving efficient construction production and control.

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REPEATABLE, SCALABLE, GLOBAL IMPLEMENTATION OF OPTIMIZED CYCLE-TIME FLOW (OCF)

Doron S. Gabai[1], Nikita S. Kennard[2], Rafael Sacks[3], Mark K. Miera[4], and Tabitha D. Cloyd[5]

ABSTRACT

Optimized Cycle-Time Flow (OCF) is a comprehensive lean construction approach to portfolio, process, and operations management of design, demolition, and tool installation projects. It comprises seven principles which teams can implement in sequence to align resources across a portfolio of projects, remove constraints, and plan for continuous uninterrupted execution of each project once it has started. Beginning in 2018, it has been applied to increasingly larger portfolios of projects in an expanding set of Intel facilities, generating consistently reliable results with up to 50% reductions in project cycle-time. A plethora of quantitative data collected through action research over five years indicate that the characteristics of OCF make it more resilient and persistent than many lean construction interventions, overcoming the various barriers to implementation discussed in the literature. The results indicate that OCF principles, vertical integration, leadership, and education make OCF repeatable and scalable. Applying these features to lean construction implementations may help practitioners achieve better results.

KEYWORDS

Action Research, Constraint Management, Last Planner® System, Optimized Cycle-Time Flow (OCF), Production Control, Strategic Integration & Planning

INTRODUCTION

Optimized Cycle-Time Flow (OCF) is a comprehensive approach to portfolio, process, and operations management of projects developed and tested within Intel Corporation at several worldwide fabs. Tool installations are short-term construction projects with very high product and process complexity. A typical semiconductor fab tool has tens, sometimes hundreds, of connections to infrastructure and material supply systems.

OCF is an improved version of the original Optimized Installation Flow (OIF). OIF achieved a 48% average cycle time reduction on a portfolio of 75 projects and 42% on 33 projects (Gabai and Sacks 2020). Gabai sought to explore whether cycle-time reduction could be scaled from the Project Implementation Team (PIT) level to the program level to learn how to better improve the system and its application through action research (Azhar et al. 2010; Lewin 1946). As is common in action research, Gabai was immersed in repeated cycles of

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devising the system, applying it in practice, evaluating the outcomes of the action, and improving it according to learning. The objectives of the research were to determine the degree of OCF impact to which it might contribute to reducing project cycle-times and to identify which aspects that make it resilient and scalable in implementation.

To date, OCF and OIF have been implemented on more than 1,700 projects at Intel fabs, in portfolios of ~300 at Kiryat Gat in Israel and ~1,400 at Intel's fab in Arizona, supporting a unique longitudinal action research effort. The wealth of experience and data collected enabled analysis of the mechanisms behind its success manifested primarily in a reduction of cycle-time of some 50% across the portfolio with significant productivity gains for trade crews. In this paper, we describe the challenges faced and review data to highlight ways in which this lean construction innovation was scaled and implemented without loss of focus, degradation of the practice, or the results over time.

OIF/OCF ORIGINS

In 2018, Doron Gabai (the lead author) was assigned to lead a subprogram with Intel Corporation construction teams. He managed three project managers, ten construction coordinators, and five hundred subcontractor trade personnel - from process-mechanical, dry-mechanical, electrical, and architectural disciplines. Although Gabai ostensibly had mature teams that previously worked together and well-defined project scopes consisting of repetitive tasks with the latest tools and techniques - his projects continued to finish late with abound excuses and unpredictable results. He was forced to request and apply acceleration actions. In retrospect, most of the mishaps could have been avoided if strategic planning had been in place to enable PIT members to catch them in a timely manner. Repeated production failures became stressors to Gabai's teams and blighted his professional track record. Gabai's mission to empower his teams to achieve their best was failing. He disliked reporting weekly failures and sought a better way - a new strategy that would:

- Benefit both project stakeholders and PIT
- Resolve constraints prior to production
- Start a project only when ready
- Not allow late production
- Not allow stopping after a project has started
- Consistently produce success and optimize flow

Gabai and his PIT began experimenting with planning strategies derived from the Last Planner® System (Ballard 2000; Ballard and Tommelein 2016), Strategic Project Leadership (Shenhar 2015), the Theory of Constraints (Goldratt and Cox 2016) and the Portfolio, Process and Operations (PPO) model (Sacks 2016) depicted in Figure . OIF integrated two project management principles (*strategic integration planning* and *target tactical planning*)**,** two LPS steps (*collaborative planning* and *constraint management*)**,** two measures design to ensure project flow at the portfolio level (*control installation start* and *ensure continuous installation*) and an emphasis on *prefabrication* (Gabai and Sacks 2020). OIF was tested on a set of 199 projects over a period of 18 months from July 2018 through December 2019. Intel teams successfully reduced installation cycle-times by 42% to 48% without adding additional resources or acceleration. This was measured as actual installation project start-to-end durations divided by planned durations, as recorded in Primavera P6. The name changed from OIF to OCF when the system operated on a portfolio level and reliably reduced cycle times when portfolios of multiple projects of a variety of types were planned in concert.

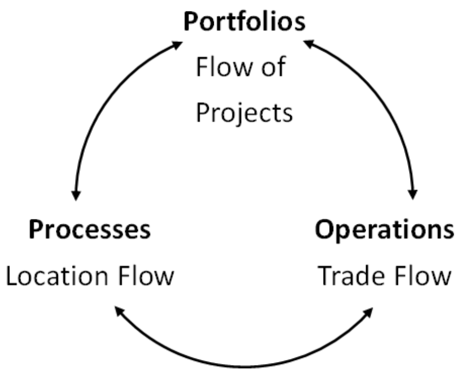

Figure 1: PPO Model - cyclical view of the relationship between project portfolios, processes and operations (Sacks 2016).

WHAT IS OPTIMIZED CYCLE-TIME FLOW (OCF)?

OCF applies seven principles to optimize flow of projects within an organization's portfolio while simultaneously reducing cycle-times and resources. It reduces the number of work-in-process (WIP) through a combination of prefabrication and constraint clearance filtering. This optimizes process flow through sound structuring of resources, task allocations, and multi-trade collaboration. OCF also applies organizational learning to maintain and repeat practices of this workflow for future projects. The Flywheel in Figure 2 depicts the seven principles. Six out of the seven principles emphasize deliberate serve as overarching strategic integration and planning that propel the flywheel. The arrows in the middle of the flywheel – trust, value, innovation and knowledge – help build and maintain flow. Achieving a reliable flow of projects and processes is one of the explicit goals of OCF and enables predictable project delivery. The principles collectively implement strategic integration and planning to enable a thorough production start in principle seven.

OCF Principles:

1. Plan & Integrate Strategically
2. Plan Tactical Targets
3. Collaborate
4. Resolve Constraints
5. Restructure Resources
6. Control Project Start
7. Ensure Project Flow

Figure 2: Optimized Cycle-Time Flow Strategy for management of projects

The sequential order of OCF principles establishes the planning and control of workflow for all stakeholders involved, from executive-level teams to production teams. Each principle requires an immediate action and builds upon the prior principle onward into the start of production in Principle VII. Table outlines the intended outcomes of applying principles within an OCF batch in a project to enhance the flow of a program portfolio. Six of the seven apply to the planning phase, which emphasizes the importance of deliberate planning.

Table 1: OCF Principles and intended outcomes.

Principle No.	Principle name	Intended outcome	Project phase
I	Plan & Integrate Strategically	Align project strategy with organizational strategy, establish 50% reduction of both cycle-time and resources	Initiation & Planning
II	Plan Tactical Targets	Written plan with percentage duration reduction target	Planning
III	Collaborate	Stakeholders' commit to OCF targets	Planning
IV	Resolve constraints	Proactively identify and resolve resource, information, procedure, material, labor, and space constraints	Planning
V	Restructure Resources	Shift skills/activities off critical path/project	Planning
VI	Control Project Start	Start only when ready by re-evaluating checklists	Planning
VII	Ensure Project Flow	Execute and maintain flow using one dedicated team "Touch the Project Once"	Execution & monitoring

OCF was developed in response to numerous problems observed in prevailing project management practices. Like many other lean construction interventions, it conflicts with existing behavioral patterns that are deeply ingrained in the traditional culture of construction. This requires paying careful attention to hearts and minds, as workforce and managers need to reset deeply-rooted ideas about production planning and control. The problems that were observed and ways in which OCF principles address them are detailed in Table .

Table 2: Production problems observed during 2018-2022 in two sites and the OCF approach to ameliorating them. Relevant OCF principles are listed in parentheses.

Problem	Description	OCF strategy
Multi-Projecting (project WIP)	Teams often struggled to work simultaneously on up to eight different tool installation projects in different locations	OCF assigns one project per team at a time. Allowing a team to focus on one project reduces distractions and overworking the PIT (*Strategic Integration & Planning, Project Flow*)
Optimism Bias and Parkinson's Law	Much time is wasted and/or unreasonable deadlines are set. Targets are set, but not discussed with the teams who are performing the work.	OCF requires ongoing collaboration between the PIT and stakeholders during strategic integration and planning; input from the PIT is solicited, valued, and shared with stakeholders (*Target Tactical Plan, Collaboration*).
Wasted Work	Teams do not finish what they started without changes and/or multiple interruptions (e.g., waiting for materials, waiting for crews, waiting for approvals)	The PIT's skill and expertise are respected and applied for constraint filtering. Projects start only when make-ready checklists are complete. OCF's six planning principles are preventative discussions that enable uninterrupted project execution and prevent rework (*Constraint management, Project start*).
Competing Priorities	Every task in a project is considered "high priority". This leads to provision of resources to complete the tasks, which denies resources from other tasks.	Knowing true priorities reduces stress on the PIT. OCF applies readiness tools to label priorities: OCF batching matches resources demonstrated capabilities with the right priorities (*Strategic Integration & Planning*).

Problem	Description	OCF strategy
Constant Change	Change in project scope is prevalent due to market demands (the need to keep ahead of competition). Most often change is introduced during a project surprising and disrupting teams' performance	OCF enables a competitive edge by reducing cycle-time. This allows freeze of scope: when a PIT starts project *i*, the scope of project *i+1* is frozen. Changes can still be made only in OCF batch *i+2* subject to thorough application of make-ready checklists. Thus, OCF establishes a stable and predictable way to introduce innovations and changes for the PIT (*Strategic Integration & Planning, Project Start*).
Inefficiency	Project 'acceleration' actions lead to inefficiency because they force trade crews to move resources from project to project, interrupting other projects in unpredictable ways.	OCF avoids accelerated work schedules that overwork the PIT and establishes consistent and ongoing work for the PIT to complete (*Strategic Integration & Planning, Project Flow, Throughput formula*).
Task Force Mode	Priority projects are assigned exclusive resources, disrupting PITs.	The OCF batching team proactively removes constraints with PIT and stakeholders' assistance, eliminating the need for 'Task Force Mode' (*Project Flow, Strategic Integration & Planning*).
Lack of Incentive	No incentive to finish projects early; we typically have not acknowledged PITs for finishing a project early	Finishing projects early and reliably give PIT time for a break and helps avoid stress. Early finishes are recognized and rewarded (*Project Flow, Strategic Integration & Planning*).
PAS Start valued more than PAS Finish	Start Progress (or Performance) Against Schedule (PAS) was prioritized. Teams were frequently successful at starting, but less frequently succeeded in finishing on time.	OCF does not allow projects to start unless ready and enables successful completion. PIT can be assured that once they start, they will finish (*Project Start, Project Flow*).
Multi-Tasking	PIT trade crews work on multiple tasks simultaneously and priorities often change. Often when welding or bending pipes, for example, teams are sent to work on different tasks (fetching materials, for example).	OCF does not allow changes to task assignments during production and enforcing make-ready conditions means the PIT can consistently complete tasks with repeatable results. This also reduces safety risks and improves quality (*Strategic Integration & Planning, Restructure Resources*).

Extensive data obtained from OCF implementations (Freeman 2022a; Miera et al. 2021) indicate the following measurable and quantifiable benefits of OCF:

1. **Increased Organizational Throughput:** Reduced project cycle-time improves project throughput in accordance with Little's Law, allowing control of work in progress (WIP). Overall, schedule execution is reduced by eliminating constraints and idle times in the strategy. This is achieved without acceleration.
2. **Predictable Delivery Performance and Execution:** OCF provides a visual representation of current projects and prioritizes OCF batches based on customers' needs through predictable delivery performance.
3. **Improved Cost Control & Cash Flow:** Reduction of the cost of resources due to reduced waiting and continuous work, thanks to strategic planning of project batches and improved schedule predictability and reliability. Resource demand is leveled, avoiding peaks that degrade productivity.

4. **Change Control:** Rather than apply innovations via short-term project scope changes. Innovations are introduced in i+2 OCF batches. This prevents interruption and disturbance to the workflow of the majority of projects.
5. **Efficient Decision Making:** OCF batching decisions are made in collaboration with project customers and support stakeholders, freezing and prioritizing per customer needs.
6. **Shorter time to market:** The overall value of the strategy when applied broadly is to reduce the time needed to bring new products to market.

The associated qualitative benefits to the company and different stakeholders include enhanced competitive advantage, operational excellence, improved communication and increased internal customer satisfaction.

EXPANDING IMPLEMENTATION

Expanding and implementing OCF required overcoming barriers identified in the literature (Bølviken and Koskela 2016). A recent study highlighted a lack of support and commitment from top management as a barrier (Moradi and Sormunen 2023). Gabai faced multiple challenges when scaling and expanding OCF beyond Israel to Arizona. However, working with co-authors Miera and Cloyd, Gabai and his team were able to demonstrate production results with sufficient throughput improvement to convince top management that OCF succeeds in engendering vertical integration. They were guided by Kotter's eight steps for leading change (Kotter 2012, Fig. 2-2 p. 23). In the OCF context, this involved:

1. Emphasizing the urgency of implementing tool installations effectively to provide a competitive edge in semiconductor fabrication.
2. Convincing management that the OCF strategy was an effective solution and explaining the benefits to PITs through their lenses.
3. Formalizing the OCF strategy and documenting it clearly.
4. Identifying and equipping OCF Champions to lead teams.
5. Convincing PIT members, both employees and subcontracted trade crews, to take the risk necessary to change their patterns of work.
6. Generating and celebrating early wins – work with the most promising candidates in each PIT, experiment with OCF to gradually optimize 50% cycle-time reduction.
7. Promoting ongoing learning and education of OCF goals per project through team collaboration, measuring results and assessing production flow for improvement.

Nevertheless, finding willing partners among project managers and production teams proved exceedingly difficult. Gabai leveraged the experience of five fearless early adopters (Montoya, Yalung, Bambauer, Miller and Lempert) – all project managers with whom he worked previously (Freeman 2022b). He met with trades and other subject matter experts (SMEs) within their PIT to engage them. This resulted in an initial set of 48 projects with an average of 48% reduction in cycle-times.

Gabai devised a strategy for the broad implementation of OCF, answering such questions as: What would the throughput look like? What are the cycle-time benefits for the program? A careful analysis of implementation barriers across teams served as possible solutions to guide this effort. The analysis is detailed in Table .

Table 3: Barriers to OCF implementation in Arizona and solutions applied.

Barriers to OCF implementation in Arizona	Strategic OCF Solutions
Contracts from previous projects set the tone for doing things the same way. Convincing trades that OCF was different to current practice, where only Last Planner® was used, was challenging	Help people understand the current reality and see the future, building a shared vision, making incremental improvements, and asking what needed to be done to make this successful. The small wins when the team hit 25% (crawl) and 33% (walk) aiming toward 50% (run) targets were celebrated – building trust.
Culture of the project ecosystem. Each team believed that others were the constraints.	Formed a coalition of the willing – following Kotter's 8th step. This is the foundation of vertical integration. We established an OCF Program Batching team that met daily to continually communicate the vision, remove obstacles.
Threading various groups together. Lack of cohesiveness, multiple teams working in silos. Focus on local optimization.	Team leaders understood that OCF was unlike other strategies. They learned that OCF is not simply tactics or objectives, and they may have recognized parts of OCF in previous initiatives such as IPD or Last Planner® System. They learned to avoid selective implementation and implement all seven principles to yield disruptive change.

OCF was performed with four PITs in 2020, and this grew to eight Arizona PITs that included design teams during 2021 and 2022. The Arizona team developed a strategy to halve the project durations using a crawl, walk, run, methodology. As each new group of trade partners was introduced to OCF, they initially set a target of a 25% reduction in duration. This allowed gradual onboarding of new trades to experiment with the owner and develop trust over time while applying the new strategy with a less demanding target. As project managers and PITs learned and grew in confidence applying OCF, targets were adjusted to a 33% reduction of duration for their next set. Finally, a set of 378 projects was given a 50% target reduction rate. Figure shows the distribution of outcomes. The 57 projects with targets of 25% achieved an average of 26% schedule reduction in practice. The 139 projects with 33% targets achieved 34% and the 139 projects with 50% targets achieved 48%. Table shows the expanding number of projects.

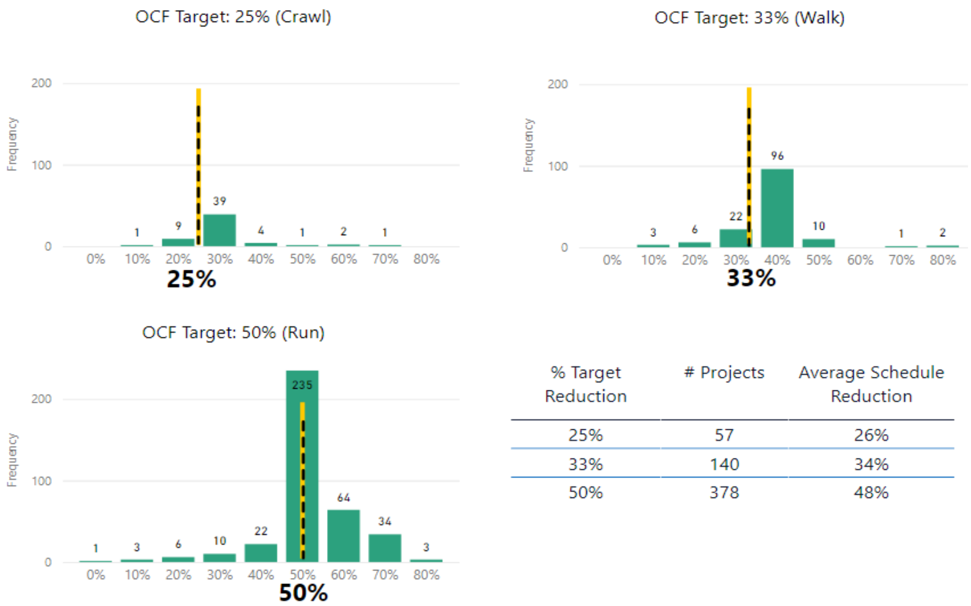

Figure 3: Distribution of duration outcomes for crawl (25% target reduction in duration), walk (33%) and run (50%) projects sets.

Table 4: Expansion of OCF to Intel's Arizona PITs (quantity of discrete projects).

Project type	2020	2021	2022
Demolition	-	281	220
Design	-	230	105
Tool Installation	48	307	268
Total	48	818	593

Over time, the Arizona OCF program yielded five times as many projects as Israel and demonstrated a 233% throughput improvement compared to non-OCF projects for Intel Corporation. Table lists the cumulative total project durations over five years. This was made possible thanks to vertical leadership and upper management changing the ecosystem culture from the top down in the organization in terms of planning and executing OCF projects. At the time of writing, the company has completed more than nineteen batches of OCF projects reducing costs and substantially enhancing revenue for Intel benefitting subcontracted trades and third-party teams. We have annotated three anecdotal comments from PIT trade members below saying the following:

- "This [OCF] program definitely shows a nice level even flow of work without the spike in manpower…that's what I got out of it."
- "All of us trade partners – the majority of us were doing well on the performance side but, every once in a while, there was a supplier or equipment delay. That's where we found our biggest challenge because then it's a domino effect on batching. So, everyone has to perform 100% for the batching to be 100% successful. I definitely felt like this last ramp that we went through was smoother."
- "Schedule wise it was successfully compared to previous ramps for sure and the profitability side you know…we did not lose money overall, the teams definitely liked the [OCF] batching program – the "get it done before we start a new task." They definitely preferred, enjoyed and liked that method of scheduling. So we're on board with this, this OCF concept for sure."

Table 5: Cumulative total project durations in days for OCF implementations of tool installation and demolition projects - baseline plan, OCF target and OCF actual days.

Baseline Plan, Target, Actual	2018 ISR	2019 ISR	2020 ISR & AZ	2021 ISR & AZ	2022 ISR & AZ
Baseline Plan project days	1,057	3,996	3,969	16,231	11,321
OCF Target project days	826	2,753	2,422	8,357	6,572
OCF Actual project days	502	2,288	2,129	8,775	6,674
% Reduction (Actual vs. Baseline)	53%	43%	46%	46%	41%

DISCUSSION

Organizations must adapt to be innovative to meet current and future demands. These innovations require projects to be better optimized for them to deliver new products or services. Hence, many organizations run portfolios of numerous projects and programs in parallel. To yield outcomes that lead the market, an organization's ecosystem should enable setting the right priorities for compatible resource allocation so that the goal of the projects can be done in shorter and more predictable cycle-times ahead of competition.

Considering the barriers to the implementation of lean construction innovations and Kotter's steps for organizational change, the OCF team at Intel focused on preparing leadership by highlighting and publicizing potential benefits to educate PIT teams - taking proactive steps to remove barriers to lean construction implementation.

LEADERSHIP AND EDUCATION

OCF has garnered engagement from top management because of active participation mandated beginning with principle number one to completion to strategically plan with a commitment to the schedule and needed resources to optimize 50%. OCF is not deployed successfully without vertical leadership support and recognition of mutual benefits for both the organizational and PIT ecosystems. Thus addressing Moradi and Sormunen's (2023) findings on lean barriers. OCF Champions, stakeholders, etc. must fully understand the organizational benefits of OCF in conjunction with the benefits of OCF for the PIT prior to attempting strategic integration and planning discussions. This helps everyone understand the "why" and the need for such a holistic production strategy.

Collaboration and the component of mutual benefits for everyone (i.e., the customer, production, and organizational teams) were focal points for reiterating the crawl, walk, run optimizations of OCF cycle-times. Miera, Cloyd and Gabai coached PMs to keep crawl, walk, run in mind as they developed target pull plans for their OCF batches. PMs had to adapt to new targets based on the OCF batch; applying Principles I and II which helped to identify OCF Champions – team members who fully grasped and accepted the strategy. Next, an OCF batching team of leaders from Intel, internal customers, and PITs worked side by side to devise an inclusive strategy at all levels of program implementation to address:

- Why are we doing this?
- What is the shared vision that will inspire and challenge our teams?
- Are we freezing the scope?
- Do we have an up-to-date target tactical plan?
- How do you turn common field constraints into a pre-defined constraint checklist?
- Are we really ready to start?
- Can we start and not stop?

BARRIERS TO LEAN IMPLEMENTATION

Many publications point out the difficulties that implementers of Lean Construction face (Bølviken and Koskela 2016; Moradi and Sormunen 2023). Lack of definition of what constitutes Lean Construction hinders both adoption and sustainable implementation from managers and crews often not having a clear idea of what is expected of them (Leong et al. 2015; Pasquire 2012). Mano et al. (2020) provide a useful meta-analysis of the literature. From some 400 causes identified, they isolated eight key barriers to Lean Construction implementation: (1) lack of commitment in the team, (2) difficulty in obtaining support and commitment from upper management, (3) resistance to change from leaders, (4) difficulty in centralizing the focus of the client's business, (5) resistance to change from employees, (6) inability to measure the progress of the Lean project, (7) decision centralization, and (8) lack of preparation by the managers to conduct the change. Six of the eight relate to leadership, and three highlight the need for a solid base amongst company leaders prior to deployment. Reflecting on our action research taken to expand implementation of OCF and subsequently to other Intel sites in the US, Far East, and Europe, one can identify how OCF defused barriers. Appendix A outlines the barriers identified and discusses how the comprehensive strategy ameliorated those barriers.

CONCLUSION

OCF implementation started with Doron Gabai attempting to bring predictability and order to the project portfolio of one Intel PIT. In doing so, he created added value for the team, for Intel stakeholders and for subcontracted suppliers. The OCF journey continues, with expansion of adoption within Intel and beyond. At the time of this writing there are three OCF sites (Israel, Arizona, and Oregon), each at a different point in their OCF journey, applying OCF to four different project types (tool install, demolition, design, and progressive build). More than 1,700 projects have been successfully delivered ahead of schedule without adding resources, funds, or time.

The barriers authors encountered mirror those identified in the literature, with leadership ranking as the top barrier. We propose the OCF strategy as a means to overcome barriers and deploy Lean Construction to project portfolios reliably, consistently, and predictably. Among the key aspects that enable OCF to achieve changed beahviours reliably are a) a set of formally defined and standardised steps that must precede the start of any project, all aimed at ensuring continuous execution without stoppages; b) a conscious effort to level resource allocations across the portfolio of projects, avoiding overloading of any critical resources; c) setting of aggressive targets for cycle-time reduction up to 50% in full implementation when compared with accepted practice, which preventing reliance on incremental adaptation in favour of the thorough fundamental realignment of the project execution strategies of PITs.

The findings of this action research may contribute to researchers and practitioners seeking a formal framework to support scalable and reliable Lean Construction implementation.

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APPENDIX A: BARRIERS TO IMPLEMENTATION

Table 6: Aspects of OCF that address barriers to implementation of Lean Construction.

#	Barriers to Lean Construction	OCF Strategic Solutions	Main OCF Principle #
1	Lack of commitment in the team	All stakeholders commit to reviewing pre-OCF results and assessing the need for changes to implement OCF strategy	I & III
2	Difficulty obtaining support and commitment from upper management	Collaboration and vertical integration commitments	I & III
3	Resistance to change from leaders	Organizations are made aware of resistance from any stakeholder as being a direct constraint	III & IV
4	Difficulty in centralizing the focus of the client's business	A clear picture of the throughput formula (Little's Law) along with strategic integration and planning of the OCF visual batches, enables consistent workflow toward the target	I, IV, VII, & Little's Law
5	Resistance to change from employees	Resistance is a form of constraint. OCF depends on collaboration and creates transparency amongst teams to effectively assess use of skills and resources to collectively remove constraints. We identified ten benefits to the PIT, mainly reducing the workload and respecting and ensuring constraint-free project implementation through Go/No Go; start only when ready checklists	III, IV, V & VI
6	Inability to measure the progress of the Lean project	OCF offers a clear percentage target of 50% optimization of cycle-time in the strategic integration and planning principle and builds the target tactical plan from Little's Law, enabling successful project control of the project prior to starting	I, II, VI & Little's Law
7	Decision centralization	The OCF batching team governs the implementation and does not rely exclusively on a single authority, thus enabling flow while simultaneously meeting targets with key leaders across the trade disciplines	II, III, VI, VII & Little's Law
8	Lack of preparation by managers to conduct the change	OCF cannot happen without all teams on board. Crawl, walk, run is a proven approach to help PITs become familiar with the new culture.	I & III

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WHAT IS THE COMPLEXITY OF PRODUCTION PLANNING AND CONTROL?

Omar Zegarra[1] and Luis Fernando Alarcón[2]

ABSTRACT

Questionable project performance is a common issue in the Architecture, Engineering and Construction industry, with one contributing factor being the degree of difficulty or complexity of the project. One effective approach to address this issue is to improve the system of production planning and control (PP&C). This strategy, as per the literature, had evolved to include up to four different types of PP&C mechanisms that are related to ´business´, ´production´, ´virtual´, and ´complex´ aspects. Nonetheless, despite the progress, PP&C still disregards various complexity-related aspects. To address this issue, we analyzed the concept of the *´Complexity of PP&C´*. This paper discusses its definition, elements, and role. It was found PP&C complexity involves three aspects: project complexity, outcomes complexity, and structural complexity. Thus, we conceptualized PP&C complexity as a feature of the behaviour of outcomes that emerge to answer project stimulus driven by the interaction between the elements of the structure of PP&C, a feature that is both a risk and an opportunity for performance improvement. This perspective offers new insights for PP&C evolution and improvement, although further work is still required.

KEYWORDS

Production planning and control, complexity.

INTRODUCTION

Projects in the architecture, engineering, and construction industry frequently demonstrate poor performance. For example, Flyvbjerg et al., (2003, 2004) studied a sample of 258 infrastructure projects worth US$90 billion and found persistent cost escalations of between 20% and 45% that were strongly correlated with the duration of the project implementation.

In this regard, one significant factor that contributes to project duration is complexity. It influences negatively performance, as noted by Baccarini (1996), Floricel et al. (2016), Luo et al. (2017), and Williams (1999). For instance, complexity is often understood as the level of difficulty encountered during project implementation, although terms such as challenging, unstable, or unpredictable are also used to characterize it (Brockmann & Girmscheid, 2007; Gidado, 1996; Jarkas, 2017; PMI, 2013).

On the other side, one effective strategy to face the poor performance of projects relies on improving the system of Production planning and control (PP&C). The PP&C is a system which aims to transform ´intended´ into ´realized´ outcomes during the project(Ballard & Howell, 1998; Mintzberg, 1978). According to Burbidge, (1990) it *"... plans, directs, and controls the material supply and processing activities*". To do so, the PP&C relies on the use of a mechanism implemented using a set of managerial processes (e.g., planning procedures, meetings,

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etc.)(Marks et al., 2001). In turn, these managerial processes relate the strategic and operational activities while trying to create conditions to deploy and drive the construction operations, where consistent work of PP&C improves operational productivity and project performance (Ballard & Tommelein, 2021; Liu et al., 2011).

Figure 1 depicts the causation of a generic model for PP&C. This model involves two main parts: outcomes and system. The PP&C outcomes refer to the production aspect, which includes the final physical product or deliverable, the construction operations and its features (e.g., labour productivity, the propagation of variability, etc.). In turn, the PP&C system describes the managerial aspect which drives the PP&C outcomes. The system receives the stimuli from the project context, inputs (e.g., information on resources, labour, tools, methods, etc.) and feedback from the performance details of operations and progress. The structure of this system involves the use of an internal mechanism(s) which is set by the use of a particular model for PP&C (e.g., the Last Planner System, Critical chain, etc). Finally, the PP&C system generates an output (which involves streams of orders, weekly assignations, etc.) that drives the outcomes and could be considered part of them.

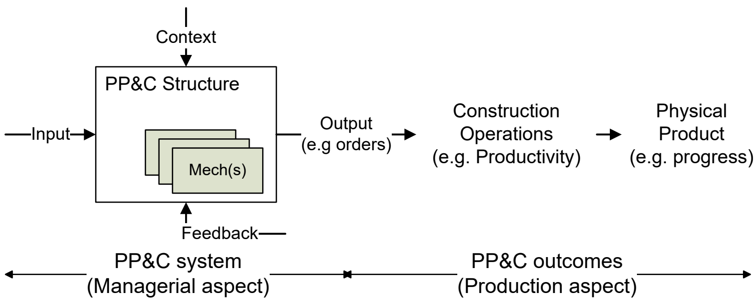

Figure 1: General causation of PP&C (for the construction stage of projects) (Zegarra 2021)

The literature suggests that PP&C use could be categorized into four types of mechanisms. The classification is based on the features and emphasis of the managerial processes used to implement the PP&C system and includes the following categories: business, production, virtual, and complex, which are complementary rather than optative(Zegarra, 2021). The business category emphasizes the use of economic/contractual processes, the production category focuses on processes for handling the workflow, the virtual category emphasizes processes for the use of virtual construction, BIM, Digital twins, etc., and finally, the complex category highlights the existence of processes for handling the interdependences between the elements of PP&C (Ibid). Thus, these categories suggest an evolution effort to improve the capabilities of PP&C and in consequence the performance of projects.

Nonetheless, despite the progress observed, the evolution of PP&C still disregards various aspects related to complexity. Where complexity is understood as a feature of the mechanism of PP&C, which emerges from its outcomes and structure. The complexity of the outcomes refers to behaviour features observed in the inputs, such as the propagation of variability (Pereira et al., 2013; Zegarra & Alarcón, 2017). Whereas structural complexity refers to the organization of a set of interdependent elements from social and process domains and their related emergent featuresover time (e.g., Zegarra & Alarcón, 2015, 2019).

In the face of an evolving AEC industry where the complexity of projects is ever-growing, the cost of doing nothing about the complexity of PP&C implies accepting both a risk and a missing improvement opportunity. For instance, Flyvbjerg, (2014)suggested that projects have moved into the TERA projects era due to the scale of their costs far beyond mega projects. Thus, this condition raises the following question:

What is the complexity of PP&C?

Thus, this study´s goals are: (1) To develop a PP&C complexity model (for the construction stage). (2) To provide a baseline theory useful for analytic generalization.

This article is organized as follows: First, the background section reviews key concepts on PP&C and Project Complexity. Then some relevant insights on the methodology are presented. After, the results section presents two models which help to describe the concept of complexity of PP&C. Finally, the main implications of the concept are discussed and conclusions are drawn.

BACKGROUND

DEFINITION OF PP&C

The PP&C plays a crucial role during project delivery, it is the system that governs the deployment of construction operations and the attainment of project goals. According to Ballard & Howell (1998) in the AEC industry, the PP&C system often is depicted as the preparation and control of schedules and their related budgets at the project level. For instance, the creation of as-planned schedules and their comparison against as-built schedules. Modern PP&C systems have been redefining this view, by describing it as a hierarchical and collaborative planning system, which involves several stakeholders and spans various levels, from operational to strategical (Ibid) or as a system enabled by the use of BIM (Schimanski et al., 2020).

According to Zegarra (2021), the literature suggests the existence of four approaches to the definition of PP&C, as the examples in Table 1 shown

Table 1: Selected definitions of PP&C (Zegarra, 2021)

View	Definition
Business	"*Project planning and control have as its broad and overall objective the prescribing and field attainment of an orderly progression within budget and time, toward the completion of project facilities."*(Halpin & Woodhead,1980 p293)
Production	*"Construction production and control can be usefully conceived and represented as consisting of three hierarchical levels roughly corresponding to … (1) aggregate production planning; (2) material coordination and work-load capacity; and (3) work order release and production unit control … the levels are (1) "initial planning"… (2) "lookahead planning", " … and (3) "Commitment planning"… "* (Ballard & Howell, 1998 p11)
Virtual	"*BIM-based production management system … is characterized by a theoretical integration model for BIM and existing construction management techniques …"* Schimanski et al., 2020 p1*)*
Complex	*"[Project control feedback structures] are managerial decisions and actions to correct poor project performance during project execution. Project controls can include process improvement, adjusting performance targets, change management, and resources management"(* Taylor et al., 2007 p1*)*

In this context, this work uses the following definition of PP&C, which is a synthesis of the definitions found in the literature:

> *´the PP&C is a Project´s function which aims to transform intended into implemented outcomes, to do so, it uses a system that interacts with the project and which relies on a particular causal mechanism(s) (e.g, a set of managerial processes), to transform strategy into operational actions through the interaction*

of persons, information, decisions, actions, processes, and technical resources while generating managerial throughput (e.g., weekly instructions)and emergent features (e.g. variability), which in turn drives and influences the deployment of construction operations over the project course´ (Zegarra 2021 p 17).

PROJECT COMPLEXITY

Complexity is a critical characteristic which influences the performance of projects. Over time its ever-growing magnitude has exposed the weakness and limitations of the managerial methods used for project delivery (Baccarini, 1996; Floricel et al., 2016; Luo et al., 2017; Williams, 1999). For instance, it influences the required levels of planning, coordination, and control, where higher complexity levels impact negatively, time, cost and quality performance (e.g., Baccarini, 1996; Floricel et al., 2016)

The definition of complexity Involves the existence of various aspects. In this work, complexity is understood as a "*property according to which, aspects such as the interactions between elements within a system structure, dynamical trends in the behaviour of its outcomes, emergent and unexpected features …., and uncertainty play a crucial role in the behaviour of the system* (e.g., Boisot & McKelvey, 2011; Dooley & van de Ven, 1999)" (Zegarra 2021 p2).

In this context, emerges the definition of *project complexity.* Although there is a lack of consensus, the concept can be described using the selected terms in Table 2:

Table 2: Project Complexity (Zegarra, 2021)

Definitions
"*The degree of difficulty faced during the execution and fulfilment of work activities and objectives over the project course* (Brockmann & Girmscheid, 2007; Gidado, 1996; Jarkas, 2017)*"* (Zegarra 2021 p3)
" A project´s feature ´… "consisting of many variated interrelated parts" and can be operationalized in terms of differentiation [of elements] and interdependency´ (Baccarini, 1996; Luo et al., 2017)*"* (Ibid)
" A feature characterized by two aspects ´… [i] structural complexity, [i.e.] the number and interdependence of elements (following a paper by Baccarini) … and [ii] uncertainty in goals and means (following a paper by Turner and Cochrane)´(Williams, 1999 p269)*, where interaction and emergence drives a structural complexity which includes uncertainty* (Cristóbal, 2017)*"* (Ibid)

The interest in project complexity has grown during the last two decades, nonetheless, its use as part of the regular arsenal of methods available in projects is under development. According to the literature (Baccarini, 1996; Cristóbal, 2017; Floricel et al., 2016; Luo et al., 2017; PMI, 2013), among the aspects currently studied, are its importance, the awareness of its role, its elements, measurement, impact, and management, where the main findings include:

- Key drivers: team and technological complexity
- Measurement: Based on conceptual frameworks (e.g., surveys) but it still lacks robust approaches (e.g. using interactions, dynamics, etc.)
- Impact: It affects negatively project performance
- Approaches currently used to face it: risk management, style of management, and capacity for adaptation.

METHODOLOGY

This study aims to provide *a preliminary theory* for future study of PP&C. To do so, it builds a mechanistic explanation (Hedström & Ylikoski, 2010) that uses a set of models and theoretical propositions to address the features of PP&C complexity. This reasoning uses the findings of (Zegarra & Alarcón, 2017, 2019) and Zegarra (2021) and concepts from a Language Action Perspective (LAP)(e.g.,Winograd & Flores, 1986), Lean Management (e.g., Koskela et al., 2002), and Complex Adaptive Systems (CAS) (Boisot & McKelvey, 2011).

The methodology follows the case study logic to state the role of the theory it aims to develop. Thus, following Yin, (1994 Chp 2), this work builds a baseline theory useful for guiding future inquiry on the complexity of PP&C (Figure 2a, step 1). The baseline, in turn, will be tested later throughout future empirical data analysis (Ibid).

The baseline theory provides a mechanistic explanation. In this regard, it focuses on building models to depict the "*cogs and wheels of the causal process through which the outcome to be explained was brought about*" (Hedström & Ylikoski, 2010 p50). Thus, the explanation integrates observations on the PP&C work, previous studies, LAP, Lean, and CAS concepts to build two models. Figure 2b describes the reasoning process used to develop the explanation (Pauwels and Di Mascio 2009).

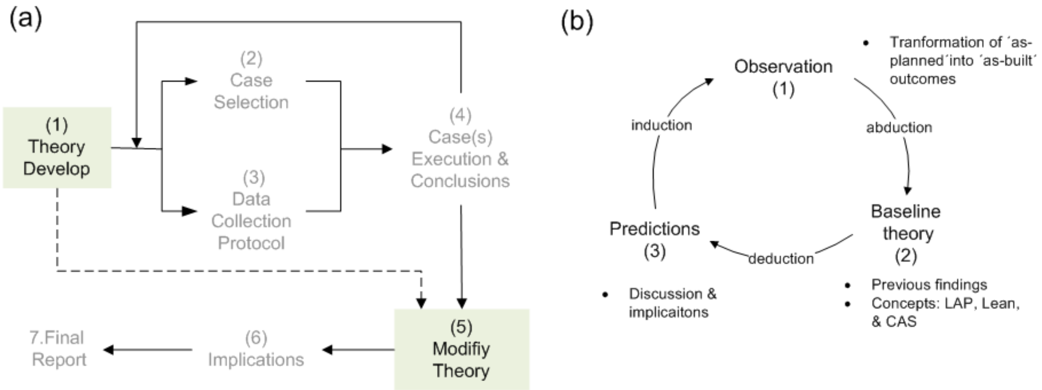

Figure 2: Research methodology: (a) Baseline theory role; (b) theory-building approach (After Pauwel and Di Mascio 2009 p13)

The following assumptions on the mechanistic explanation must be noted: First, it conceptualizes human action using LAP. Then, it uses a Lean view to model the value stream of PP&C. Finally, using CAS tools and concepts it describes the behaviour of outcomes. The CAS tools and concepts include the "Ashby Space" (Boisot & McKelvey, 2011), the *´law of requisite complexity´* (Ashby, 1957; Boisot & McKelvey, 2011), variability propagation concepts (Zegarra & Alarcón, 2017) and complex adaptive ideas about PP&C modelling (Zegarra & Alarcón, 2019).

PP&C COMPLEXITY MODEL

The following models describe the different aspects of PP&C complexity. The first model (Figure 3) describes a general view of the causation enabled by the PP&C, highlighting its complexity-related elements (e.g. emergent features, feedback linkages, etc.). The second model (Figure 4) describes the behaviour aspects of the relationship between the complexity of the project and the complexity of the PP&C system and outcomes.

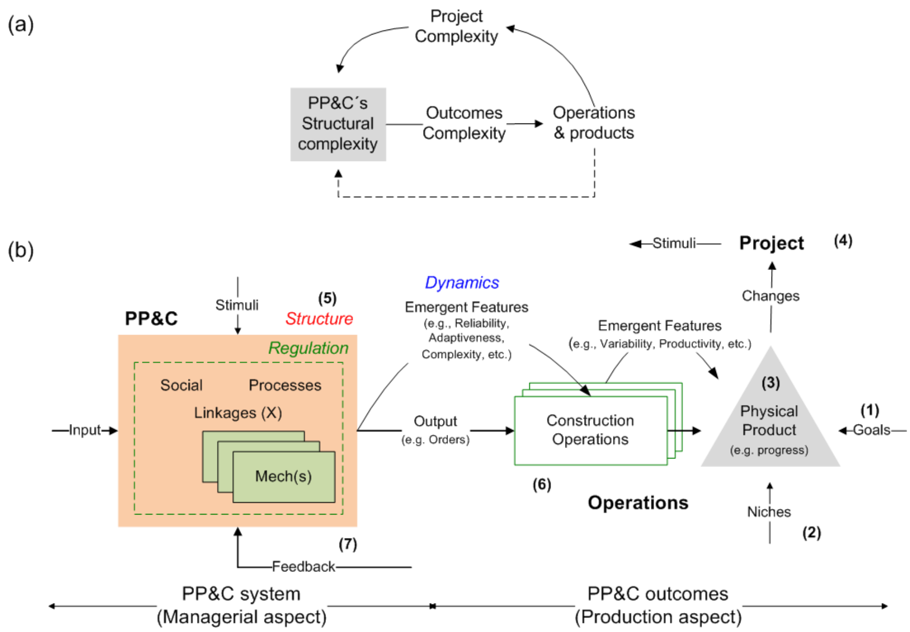

Figure 3: General causation of PP&C and its complexity features (After Zegarra 2021)

GENERAL CAUSATION MODEL

The model in Figure 3 describes the relationship between PP&C, Operations and Project. The model considers them as three coupled and hierarchical systems. The Project level is the most external, while PP&C is the most internal. At the Operations level, the outcomes of PP&C answer project stimuli. In this way, the complexity of PP&C can be divided into three related categories, project complexity, structural complexity, and outcomes complexity (Figure 3a). Figure 3b details the different aspects of the relationship, explained as follows:

Project complexity describes any element located beyond the construction operations level but within the project´s boundary. For instance, engineering, procurement, etc. or any other aspect carried out as part of the project

Structural complexity describes an attribute of the PP&C system´s structure. It includes elements from social and process domains, the linkages between elements, emergent features, and mechanisms used to provide managerial causation. The handling of the structure during the project involves a regulatory effort.

The outcomes complexity describes the behaviour attributes of the PP&C outcomes. These include managerial output (e.g., the emission of orders, weekly assignations, etc.) and its associated emergent features (e.g. the assignations´ reliability), the deployment of construction operations and their related emergent features (e.g., their productivity, variability, etc.), and finally the generation of physical products. The model names the managerial output and the emergent features as dynamics

Finally, the model depicts a progressive adaptation process of PP&C, operations, and projects. Thus, following Ellis (2008), to attain a certain goal (1) (e.g., an as-planned goal), the PP&C outcome fulfils a certain behaviour niche (2), through the generation (6) of a physical product (3) (e.g. an as-built result), all of these steps generate feedback (7) on the structure of PP&C. Step 3 introduces a change in the project´s conditions (4), which in turn generates a new stimulus that influences the operational level and the PP&C structure (5). Given the hierarchical and coupled nature of the model, the adaptation process suggests a double-loop interaction (Sterman, 2000). The internal loop involves PP&C and operations, whereas, the external loop involves the operational and project levels. This mechanism may drive the co-evolution of PP&C, Operation, and Project over time.

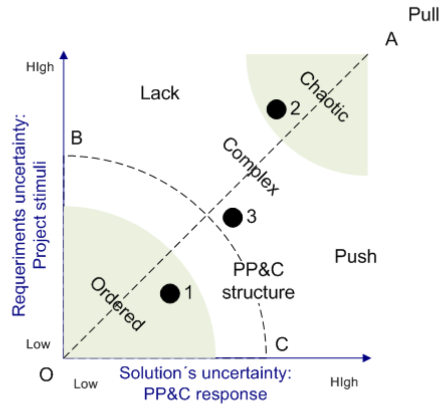

Figure 4: Relationship between Project and PP&C (after Zegarra and Alarcón 2019)

BEHAVIOUR MODEL

Figure 4 presents a behaviour model for PP&C complexity. It relates project complexity and PP&C complexity aspects (Figure 4). The model also provides insight from a lean perspective, based on a comparative ratio between stimuli and response.

Figure 4a describes the relationship between the complexities of the project and its PP&C system. Thus, following Boisot & McKelvey (2011): The X and Y axes describe the project stimuli and the PP&C responses respectively (e.g., in practical terms, these axes could use as stimuli data from as-planned schedules and as response as-built schedules data); The curve BC describes the boundary of the PP&C structure; The line OA describes a state of equilibrium between stimuli (Y) and response (X); Each black dots describe a pair of values x,y over X and Y axes; Finally the space also depicts three potential states of behaviour: ordered (i.e., linear and regular), chaotic (i.e, random) and complex (i.e., a transition between the previous two states and which mix their features), where for instance the relationship x,y for the dot 2 exhibits chaotic behaviour.

In addition, the model in Figure 4 also provides a behaviour insight from a Lean perspective. Thus, following Zegarra & Alarcón (2017, 2019): OA reveals an ideal pull relationship between Project stimuli and PP&C response (i.e, response/stimuli = 1), whereas the areas OAX (below OA) and OAY (above OA) respectively depict "push" (i.e., response > stimuli) and "lack" (i.e., response < stimuli) behaviours for each pair of x,y values. This interpretation is based on the behaviour of a divisive ratio used to express the nature of the activity between stimuli and response, for an x,y point over a two-dimensional diagram (Lindemann et al., 2009 p202). Finally, as a summary, it can be said for instance, that dot 3 is located beyond the structure of PP&C, and exhibits a complex behaviour, with a push relationship between stimuli and responses.

DISCUSSION

This study aims to provide an answer to the question, what is the complexity of PP&C? To do so, it presents a model that depicts and explains the nature of this concept. The complexity of PP&C is understood as a characteristic that influences performance and that involves three aspects: ´outcomes complexity´, ´structural complexity´ and ´project complexity´. The model developed in this study depicts the complexity of PP&C as a relationship between project complexity (stimuli) and the complexity of PP&C outcomes (responses), a condition which in turn is regulated by the structural complexity of PP&C. This relationship may behave exhibiting an ordered, chaotic or complex regime. The complexity of PP&C reveals both, a risk and an opportunity for PP&C performance and improvement.

The complexity of PP&C is a behaviour feature. In this regard, it could be observed in ´*the behaviour of outcomes that emerge to answer Project stimulus, outcomes which in turn emerge driven by the interaction pattern between the elements of the structure of PP&C*´(Zegarra 2021 p17). This understanding involves the presence of three aspects: ´*project complexity*´ (i.e., the behaviour beyond the boundary of PP&C), ´*outcomes complexity*´ (i.e., the behaviour pattern observed in the PP&C outcomes), and ´*structural complexity*´ (i.e, the hierarchical organization of interdependent elements which configure the PP&C system). The complexity of the outcomes and structure are behaviour features of the mechanism used to provide PP&C in the project. This mechanism relies on the implementation of a managerial system which in turn drives the generation and deployment of various types of outcomes. This causation generates an interaction with the project through a progressive adaptation.

Project complexity describes the behaviour beyond the boundary of PP&C. It includes a set of interacting elements, which in turn, can be understood as complex adaptive systems (Choi et al., 2001). These elements interact with the PP&C over the project.

Structural complexity is an emergent attribute of PP&C. Where the structure refers to the set of interrelated elements used to implement the system driving the outcomes. Thus, the complexity of the structure describes a hierarchical organization of interrelated elements from social and process domains (e.g., team members, managerial processes, meetings, etc.) and emergent features organized to provide the PP&C.

Outcomes complexity is a behaviour pattern in the outcomes of PP&C. These outcomes may include managerial throughput, construction operations deployment, physical products or deliverables, and emergent features. The complexity of outcomes is a feature observable over the dynamic behaviour of these elements. For instance, if the managerial throughput (e.g. the set of weekly assignations) is understood as a stream of conversations used to guide the deployment of the operation, the behaviour of this stream may exhibit ordered, chaotic or complex behaviour features.

The complexity of PP&C involves an interaction between the project and PP&C. Figure 4 represents different degrees of the state of this interaction using black dots. The stimuli (Y-axis) on PP&C represent the project complexity, whereas the response from PP&C represents its outcomes complexity (X-axis). The relationship between response and stimuli is constrained by the structure of PP&C. This relationship exhibits different degrees of behaviour which span from an ordered regime, up to a chaotic one, passing through a complex state.

The model also provides insight into the behaviour of PP&C using a lean perspective. According to Lindeman (2010), over a two-dimensional diagram, a divisive ratio expresses the level of activity between stimuli and response.

The ideal behaviour for the complexity of PP&C may emerge within its structure boundary when this is located in the complexity zone close to the edge of the chaotic zone. The following reasoning elaborates on Boisot and McKelvey (2011) to explain the behaviour of PP&C: The regulation of the system structure is dynamic and involves a change of form and position. For the PP&C complexity model, this means a change of position of BC, where it can move closer to the ordered or chaotic estate driven by a change of capability in the structure (e.g. by the addition of resources). The behaviour located beyond this boundary could be problematic and difficult to sustain because it overcomes the available PP&C system capability. Also during this process, the boundary BC has the potential to change its shape (i.e. $OB \neq OC$), as the PP&C structure becomes better suited to face more stimuli with less use of resources (i.e., $OB > OC$). Thus, in the case of PP&C, the optimum level of behaviour arises when the boundary of the system is located in the complexity zone, while its structure closes to the edge of chaos, along with a response/stimuli relationship prone to pull behaviour.

A practical target for the behaviour model may be located within a band over the equilibrium line and around the boundary of the PP&C structure. According to Boisot and Mckelvey (2011), this behaviour in Ashby´s space involves a mixture of exploration (i.e., in the lack area) and exploitation (i.e., in the push area). The behaviour of PP&C is dynamic and evolves as the project progress, thus it seems unlikely that every single dot will be located within the boundary, instead some exploration may be needed to improve exploitation. The findings of Zegarra and Alarcón (2019) suggest a behaviour in this way.

The complexity of PP&C is both, a threat and an opportunity for improving PP&C performance. To survive a system must adapt to its environment. Thus, following Ashby´s (1957) law of requisite variety, restated by McKelvey & Boisot (2009) "*... to be efficaciously adaptive, the internal complexity of a system must match the external complexity it confronts*" (Boisot & McKelvey, 2011). During this process, managing the use of resources to answer stimuli may involve a *stimuli simplification* (i.e., using fewer resources) or a *response complexification (i.e., using more resources)*. In this way, a productive PP&C (i.e., both, effective and efficient), which properly adapts and co-evolves with the project´s requirements proper handling of complexity is critical.

Paying attention to complexity is an opportunity to improve the performance of PP&C. Interaction is responsible for the emergence of features such as variability, self-organization, and scalability, features have the potential to generate negative or positive outcomes (Boisot & McKelvey, 2011). Proper handling of interactions could be used to provide a positive impulse or to control a negative effect of these features on the system's behaviour (Choi et al., 2001)

The main limitations of this work include: The study´s scope of work focuses on the construction stage of AEC projects. The studies on which this work is based were conducted on high-rise buildings and housing construction projects which used the LPS.

CONCLUSIONS

In the AEC industry, one effective strategy used to face the poor performance of projects is to improve the PP&C system. In this context, the complexity of PP&C is a characteristic which influences the performance of this system. This concept involves three aspects: project complexity, outcomes complexity, and structural complexity. The relationship between them helps to describe the behaviour of PP&C in terms of ordered, chaotic, and complex states. Complexity represents a risk and an opportunity for the improvement and evolution of PP&C. The PP&C complexity concept suggests a route to expand the theory of Lean Project Management (based on the joint use of lean and complexity science concepts), especially to explain and guide the building of new PP&C mechanisms to face the different challenges of Construction 4.0.

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LOCATION-BASED WORK SAMPLING: FIELD TESTING AND UTILITY EVALUATION

Cristina T. Pérez[1], Stephanie T. Salling[2], and Søren Wandahl[3]

ABSTRACT

Visual management has been developed and used by Lean practitioners to enhance communication and control operations and processes. Lean construction, as a process-focused approach, and emerging IT tools have the potential to transform and facilitate construction operations. The authors of this paper have previously presented a prototype adaption of the work sampling technique, called location-based work sampling, based on the results of a case study. However, the utility of this visual management tool has not yet been tested. Thus, this research aims to assess how the tool can provide managers with helpful information for decision-making. The paper presents the second learning cycle of a research project that adopted the Design Science Research strategy. The second cycle includes five steps. The first four steps consist of the application of LBWS, and the last step represents the evaluation: (1) clarifying work activities & workspaces; (2) data collection; (3) data visualization; (4) data analysis; (5) tool evaluation. The assessment results show that the tool, to a high degree, fulfills the six requirements of a digital visual management practice. However, the assessment also concludes that further development is needed to fully understand user needs and integrate the tool into daily management routines and processes.

KEYWORDS

Location-based management, visual management, waste, work sampling, geographic location observations.

INTRODUCTION

Visual Management (VM) can be defined as a set of practices that support visual communication by adopting different visual devices (Tezel et al., 2016). Lean practitioners have developed and used VM and its tools to enhance communication and control operations and processes in real time (Parry & Turner, 2006). Among the benefits of VM is that it directly supports other management efforts, such as production management, safety management, performance management, and workplace management (Tezel et al., 2016). Moreover, the use of VM tools reduces feedback time for action taking (Alvarez & Antunes Jr., 2001). Tezel et al. (2015) have investigated the advantages of VM as a managerial strategy that can benefit a project in aspects such as transparency, ease of information flow, and minimizing complications in communication.

Although VM tools have been used in the construction industry for a while as signs, color coding, and hazard elements, there is a significant potential for implementation at managerial

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levels in combination with Information Communication Technologies (ICT) (Tezel et al., 2016). Some researchers have integrated IT and tools with VM to improve efficiency and communication in construction projects. Some examples of these approaches are: (1) Integration with Building Information Modeling (BIM), named KanBIM (Sacks et al., 2009); (2) Integration with BIM-based sheet (Matta et al., 2018); (3) Digital Last Planner System (Conte et al., 2022; McHugh et al., 2022; Pikas et al., 2022); (4) Visual Management to support design planning and control (Pedó et al., 2022); and (5) Construction progress monitoring (Álvares & Costa, 2019).

Some of those VM tools have been converted into successful IT-based prototypes. In the prototypes, information visualization interfaces (often BIM models) are displayed on large touch-screens in the field and supported by a Lean construction engine (e.g., a virtual Kanban system linked to the Last Planner System by Ballard (2000)) connected to the existing main-servers and Enterprise resource planning (ERP) systems. Although useful, those prototypes do not fully illustrate the extensive potential of the combined use of Lean construction techniques and emerging IT systems (Tezel & Aziz, 2017).

As a new approach, "the present authors" (year) adapted the traditional Work Sampling (WS) technique by adding geographic information collected using mobile computing to the random observation, creating the VM tool named Location-based Work Sampling (LBWS).

"The authors" (year) defined LBWS as a visual, graphical approach that facilitates sharing information obtained during the WS application, based on adding geographic location information to the random observations, named geo-located observations. The visual technique shows the observations made on construction trades and work categories in the foreground and job site spaces in the background.

The authors of this paper previously presented the prototype adaptation of the WS technique based on the results of a case study. However, the utility of this VM tool using IT has not yet been tested. Thus, this paper aims to assess how the tool can provide job site managers with useful information for decision-making. This is an ongoing research project, so the evaluation of this new WS adaptation was exclusively performed after the field testing in one construction project.

RESEARCH METHODOLOGY

The present authors adopted the Design Science Research (DSR) strategy (Lukka, 2003) for conducting the research project. DSR aims to produce innovative constructions, called artifacts, to solve real-world problems and to contribute to the theory of the discipline in which it is applied (Lukka, 2003). This project's artifact consists of the adaptation of the WS technique, called LBWS, previously defined in the introduction section.

The research process of designing the artifact is being developed during the realization of three learning cycles, named Cycles 1, 2, and 3 (Figure). During each cycle, the four main phases that categorize this DSR were conducted. The four phases are: (1) understanding; (2) construction; (3) analysis; and (4) evaluation. The four DSR phases organize different approaches carried out by the research team in various rounds of visits in the same construction site. For that purpose, the authors used the Case Study (Yin, 2003) as the primary research method, as case studies offer flexibility for explorative and theory-building research in real-life contexts.

During the first learning cycle, the first version of LBWS was developed (Authors, year). The case study's findings led the authors to identify the utility of adding geographical location to the WS technique. The present paper focuses exclusively on presenting the results of the second learning cycle, comprising the second field test and its evaluation (see text in the rectangle highlighted in Figure 1).

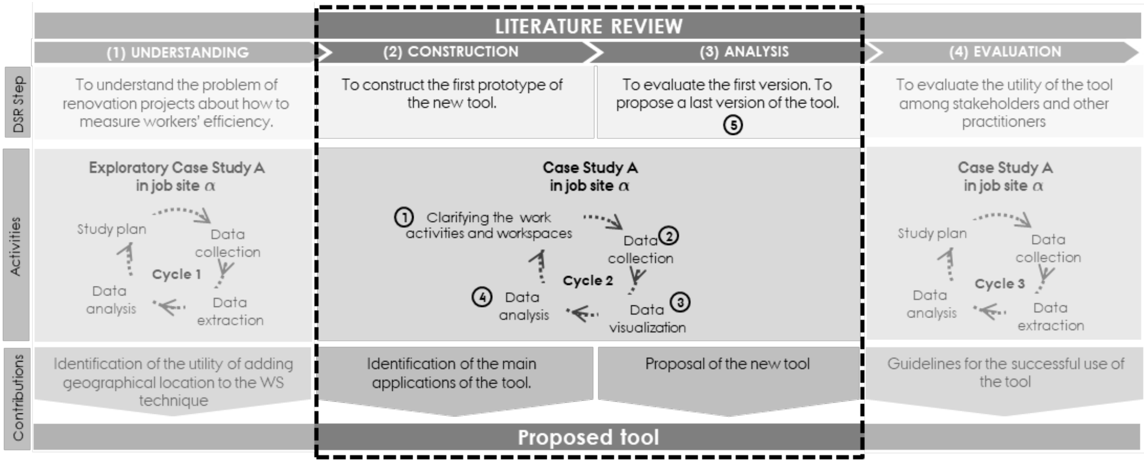

Figure 1: Research Design

CASE STUDY DESCRIPTION

The case study consists of a renovation project of 24 five-story housing buildings, a total of 597 housing units, originally constructed from 1950 to 1970 in Roskilde, Denmark. The case organization is one of the main contractors in the building sector in Denmark.

The contractor rented a façade scaffolding with plastic covering the entire temporary structure for each building under renovation. The scaffolding of some buildings is interconnected to facilitate workers' movement among the buildings. The scaffoldings included a cabin as the primary lift solution for material transport. Moreover, a mobile crane was used for lifting windows using hooks for installation and pallet lifts for transportation.

The main renovation tasks were conducted outside the buildings from the façade scaffolding and were mainly related to carpentry work, such as replacing windows and roofs, and painting work. Installing new ventilation and electricity systems represented the only two inside renovation activities. The contractor company placed modular containers within the job site for storage, administration, and changing rooms. The main material storage area, destined for inventory deliveries, is located next to the administration containers. Several work tents were installed at ground level next to the buildings under construction for conducting support activities, such as painting wood panels before installation, cutting steel profiles, cutting wood panels, etc.

RESEARCH DESIGN

Cycle 2: Application of the LBWS and Evaluation

The second cycle presents five steps (see numbers in Figure 1). The first four steps consist of the application of LBWS (Figure 2), and the last step represents the evaluation: (1) clarifying the work activities and workspaces; (2) data collection; (3) data visualization; (4) data analysis; and (5) tool evaluation.

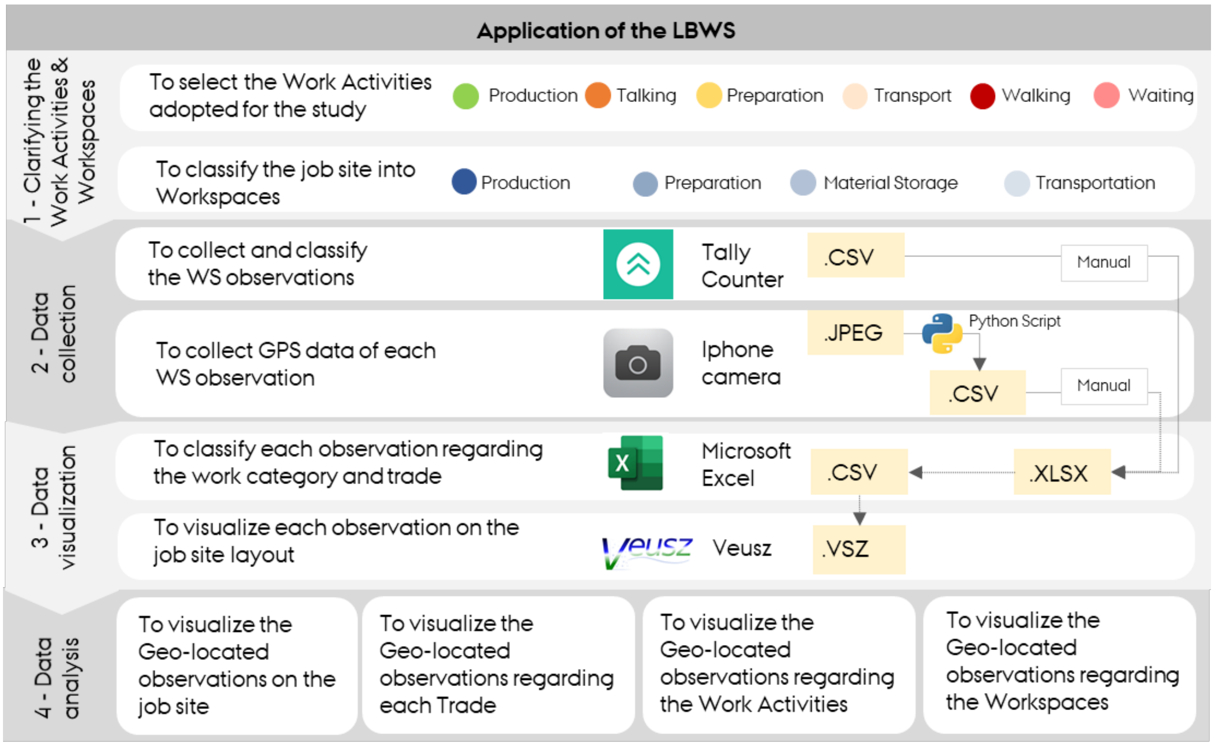

Figure 2: Application of the LBWS

Step 1: Clarifying the work activities and workspaces

The authors classified the activities of each trade observed on the job site during the first day of job site visits, named Day 0. In this study, a six-work categories classification was adopted to keep consistent with previous WS studies carried out by the research team as part of a long-term research project. The six categories are: (1) production, e.g., installing gypsum boards on the roof; (2) talking, e.g., discussing the installation process; (3) preparation, e.g., measuring with a ruler the gypsum boards; (4) transportation, e.g., carrying tools and materials; (5) walking, e.g., moving empty-handed; and (6) waiting, e.g., delaying action until receiving material.

Regarding the job site locations, this study adopted the following workspace classification: (1) production workspace, this being the buildings under renovation and the scaffolding area; (2) preparation workspace, represented by the area surrounding the production workspace; (3) material storage workspace, consisting of the container's area; and (4) transportation workspace, consisting of the area 1 and the material storage area.

Step 2: Data collection

Data was gathered in two rounds of visits, Round 1 and Round 2 (see Table 1). The data collection lasted seven days in Round 1 and five days in Round 2 (8.5 hours/each) from 07:00 to 15:30, excluding breaks: coffee break (09:00 to 09:15), lunch break (11:30 to 12:00), and coffee break (13:30 to 13:45). The observers used a smartwatch to track the position during the random tours to guarantee that all the workspaces were observed. Although the time spent in each workspace was not the same during each tour, the results presented a relatively homogeneous sample.

The scope of the observations was limited to the trades that conducted their activities outdoors (N) during the period of visits. Those trades were: (1) Carpenter (N_1); (2) Mason (N_2); Electrician (N_3); (4) Ventilation (N_4); (5) Scaffolding (N_5); (6) Painter (N_6); and (7) Demolish (N_7). The research team made the observations from the scaffolding (from the façade and roof level) as interior tours were not possible due to the presence of the tenants.

Table 1: Data collection characterization

Description	Period	Visits	Geo-located samples	Con. Interval	Sample (N)
Round 1	Weeks 45 & 46, 2021	7 visit days 8.5h/visit	n = 993 samples 142 average per day 39.8 std. deviation per day	95% ± 2%.	N =40 workers N_1=13 carpenters
Round 2	Week 20, 2022	4 visit days 8.5h/visit	n = 689 samples 172 average per day 41.2 std. deviation per day	95% ± 2%.	N ≈ 40workers N_1=13 carpenters

The research team used several digital devices to collect data during the random tours. A tablet was employed for separating the observations according to the six-work categories classification using the application "Counter – Tally Counter" by Tevfik Yucek (Apple, n.d.). A tally counter is a digital number clicker used to count something incrementally. The Counter application allowed the researchers to digitally record each observation with an exact time and export this data in a Comma-Separated-Values (CSV) format.

A mobile phone was used for taking pictures of each observation. The purpose of the photo was to collect the geographic coordinates from each observation. Despite the fact that the coordinates represent the location of the observer instead of the task observed, this difference does not impact the results since the photos were taken as close as possible to the worker. At no time were individuals' faces or other identifiers registered; The authors extracted locations and additional metadata (timestamp and file name) stored using the Exchangeable Image File Format (EXIF) Phyton library. EXIF is a standard that specifies the formats for images for recording technical details associated with digital photography (EXIF.org, n.d.). Thus, each geo-located observation contained the following associated information (Table 2): (1) photo; (2) timestamp; (3) trade observed; (4) work category; and (5) geographic coordinates, consequently, workspace category.

Table 2: Example of information associated with each geo-located observation

Photo	Time Stamp	Trade observed	Work category	Geographic coordinates	Workspace category
IMG-5548.JPG	2021.11.18; 13:33:05	Carpenter	Production	Lat 56.089999; Lon 12.309999; Alt 58.930754	Production workspace

Step 3: Data visualization

The data extracted from the devices during the random tours was visualized using the Veusz program. Veusz is a free scientific plotting and graphing program for producing 2D and 3D plots (Veusz, n.d.). This allowed the researchers to plot each geo-located observation using a graphical 2D user interface. The authors collected the coordinates of the job site facilities and buildings using a smartwatch and converted them to a visual layout using the RouteConverter program. RouteConverter is a free Global Positioning System (GPS) tool to display, edit, and convert routes from several different file formats (RouteConverter, n.d.). The list of job site coordinates was exported into a Microsoft Excel Open XML Spreadsheet (XLSX), converted into a CSV format, and then imported to Veusz. Hence, Veusz allowed visualizing the position of each observation on the job site layout. In this study, the analysis aimed to identify how and where the workers spent their time.

Step 4: Data analysis

The research team conducted the following four types of data analysis: (1) Visualization of the geo-located observations on the job site layout; (2) Distribution of the geo-located observations per trade; (3) Distribution of the geo-located observations per work activities; and (4) Distribution of the geo-located observations per workspaces.

Step 5: Evaluation of the LBWS

The utility of the LBWS was assessed according to its ability to accomplish its objectives. The objectives of this adaptation of the WS techniques are: (1) to facilitate the sharing of information of the WS technique; and (3) to support decision-making. The assessment is based exclusively on the empirical study presented in this paper. The set of six requirements that a VM should contain proposed by (Pedó et al., 2022) was used to assess the first version of the tool by the present authors.

Table 3: Set of six VM requirements (Pedó et al., 2022)

VM requirements	Definition
(R1) Simplicity	It is concerned with how easy it is to use a VM practice based on a clear understanding of its objective or function.
(R2) Standardization	It is related to whether there is repetition in using devices, i.e., regularity of information units, which can support accurate information delivery.
(R3) Availability	It is related to making updated information available at the right time and in the right amount, making it easy to prioritize information.
(R4) Accessibility	It considers how easy it is to access the information, i.e., if the information is located in the right place.
(R5) Flexibility	It is related to: (i) how easy it is to make changes, i.e., the possibility of adapting devices and practices according to the users' needs over time; (ii) how easy it is to update the information, i.e., changes can be quickly displayed in the device
(R6) Traceability	It is associated with easy storage of information and tracking its origin.

RESULTS

LBWS RESULTS

The LBWS results focus on the discussion of the use of the tool for the four sorts of data analysis previously presented.

Visualization of the geo-located observations on the job site

Figure 3Figure 3illustrates the distribution of the geo-located observations from one day of data collection from Round 1 and Round 2. There are 140 data points from Round 1 and 224 data points from Round 2. In Round 1, the carpenter trade constitutes a larger part of the observations than in Round 2.

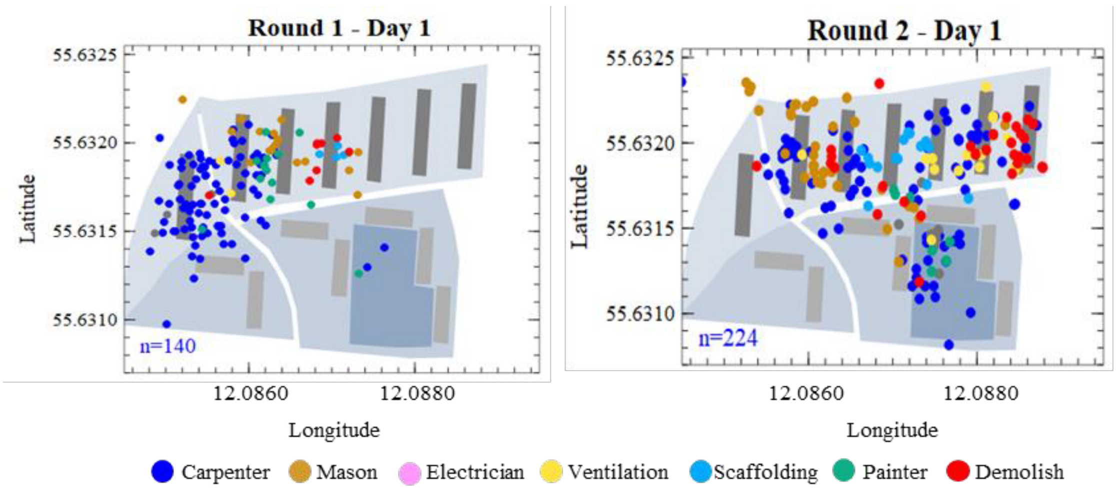

Figure 3: Geo-located observations of all trades during Day 1 of Rounds 1 and 2.

The visualization shows that there are not many similarities between the data from the two visits. During Round 1, most of the observations were concentrated on and around four of the apartment buildings, especially the building furthest to the left on the job site. Some observations were obtained in the transportation area south of the four buildings, and a few were recorded in the storage area. During Round 2, the observations were scattered across a larger part of the job site. The workers were seen on the scaffolding of almost all of the buildings as well as in the preparation workspaces between buildings, and a significantly higher number of observations were recorded in the material storage area compared to during Round 1.

Distribution of geo-located observations per trade

The geographic distribution of observations can be analyzed for each trade individually. In Figure 4, only the observations of the carpenter trade are included. As for the distribution of observations for all trades, the observations of carpenters are highly concentrated in one area during Round 1 as opposed to Round 2, where the observations are distributed across most of the job site. This means the carpenters were working in many different places during the visits of Round 2, both in the buildings and in the material storage area. The many workplaces also led to more observations in the transportation areas, as the carpenters needed to move between buildings more often.

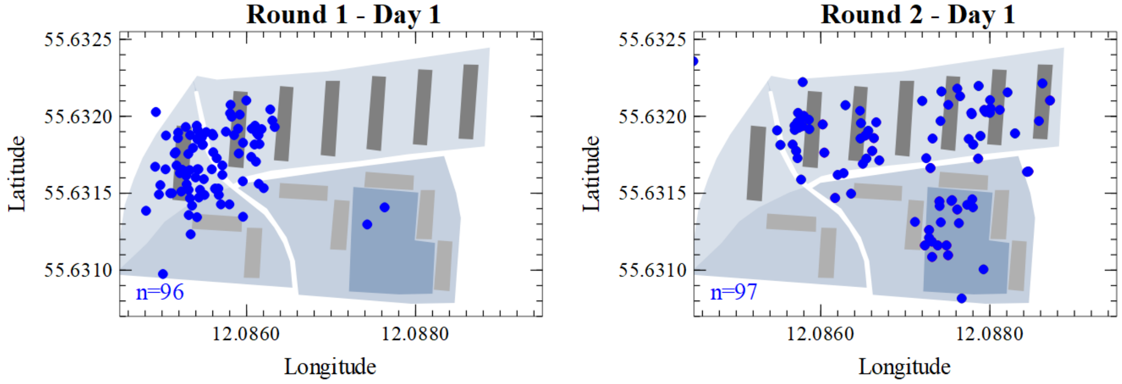

Figure 4: Geo-located observations of carpenters during Day 1 of Rounds 1 and 2.

Distribution of geo-located observations per work activities

In Figure 5, the observations of the carpenter trade have been categorized according to the work activity observed. The overall distribution of observations of the six work categories is shown in the pie charts.

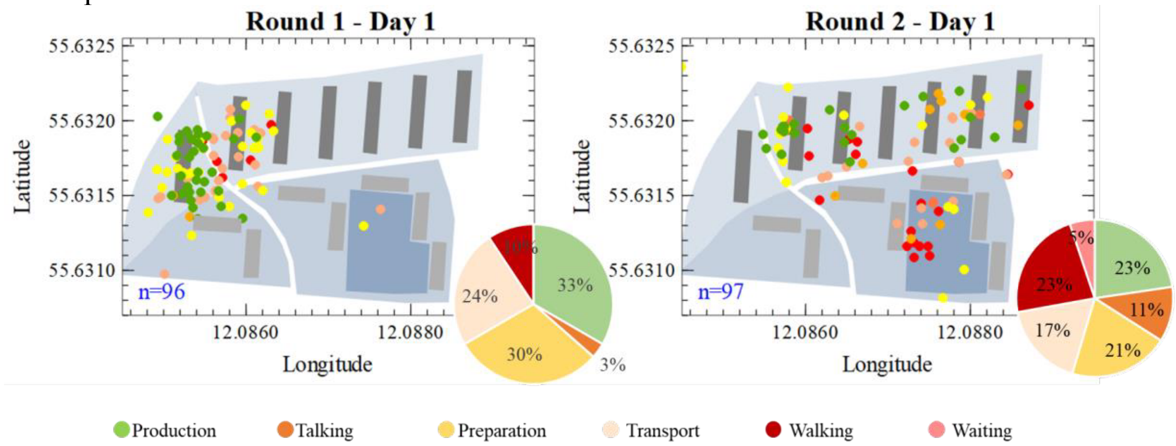

Figure 5: Positions of the carpenters' WS categories during Day 1 of Rounds 1 and 2

As seen in the figure and explained above, there were more observations in the transportation and preparation areas during Round 2 than during Round 1. The work being done in these areas is mostly non-value-adding activities such as walking and transportation, thus, the share of time spent on value-adding activities is significantly lower for Round 2 than for Round 1.

Distribution of geo-located observations per location

In Figure 6 (left), the positions of the carpenter trade observations for observation days 1 to 4 of Round 2 are illustrated. The coordinates of each observation are based on the geo-location of the photo taken of each work sampling observation. As the geo-location of each photo also includes a precise altitude value, the WS observation can also be distributed per level of each building, cf. Figure 6 (right). This visual information can serve multiple purposes, e.g., compliance checking of the location-based schedule and checking if carpenters were working on the location that was planned.

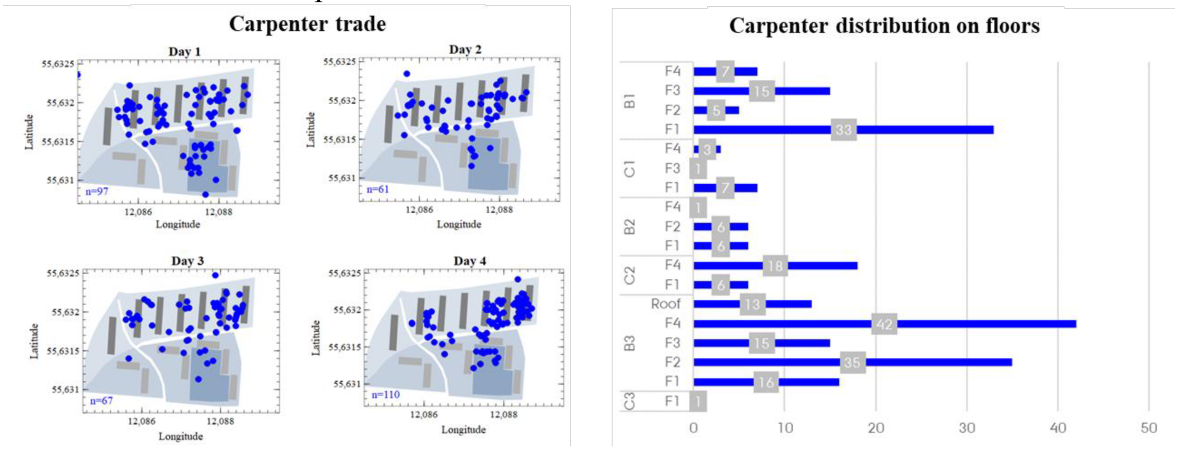

Figure 6: Longitude and latitude positions (left) and altitude (right) of WS observations for the carpenter trade per for round 2

In combination, these four types of visual data analysis of the location-based work sampling data can be used for many different purposes, such as documentation and analysis of plan and production system efficiency. This visual data can feed the production planning and control system and serve as VM to further improve the production system.

LBWS EVALUATION

The first requirement was simplicity, which is defined as how easy it is to use a VM practice based on a clear understanding of its objective and function. The objective of LBWS is to provide information obtained during the WS application based on adding geographic location information. The visual technique shows the observations made on construction trades and work categories in the foreground and job site spaces in the background. A number of different functions of LBWS have been demonstrated in this paper, and the visual representation of these functions is considered easy to comprehend.

The second requirement is standardization, which is related to whether there is repetition in using devices, i.e., regularity of information units, which can support accurate information delivery. This is very important for the operational level, as team members must be guided on how to use the practice correctly, allowing autonomy and valid data simultaneously. As the practice is still novel, standardization is ongoing. However, the data lakes are standard, i.e., geo-location, WS categories, site layout, etc. Thus, applied in repetition, the information provided to users holds a large degree of standardization.

Availability is the third requirement and focuses on making updated information available at the right time and in the right amount, making it easy to prioritize information. For all the four functions described in LBWS, it is easy to update the data file and produce new visual outputs. Both Work Sampling data and Location data are based on .csv files, cf. Figure 2. However, the update process currently includes some manual steps. Filtering the information is easy in the Veusz program.

Accessibility is the fourth requirement and is defined as how easy it is to access the information, i.e., if the information is located in the right place. The main users of the LBWS practice are likely also those who orchestrate the data collection and carry out the data analytics. Thus, the main users have very good accessibility to the information provided by LBWS.

The fifth requirement is flexibility, which is related to how easy it is to make changes and adapt to the user's needs. As described, the four functions of LBWS are the practice's main utility. Other functions and analyses might surface, and it should be easy to amend to such user requests, as the process of data acquisition and data analytics is simple and standardized, cf. Figure 2. However, some of the steps of converting data require insight and knowledge of the data collection and are also quite time-consuming.

Traceability is the sixth and final requirement. It is associated with easy storage of information and easy tracking of the origin of the information. The system has full transparency, i.e., every graphic representation is directly linked to one or more data sets that correspond with time, place, trade, etc. The practice does, however, not have a versioning system, meaning old versions cannot be accessed if the users have not saved these deliberately. In Table 4, a summary of the evaluation of the six requirements' fit with LBWS is presented, based on a high/medium/low assessment.

Table 4: Assessment of the six VM requirements on LBWS

VM requirements	High/Medium/Low evaluation of LBWS
Simplicity	Evaluated as high. A clear objective of LBWS is present. Several different functions with a clear visual representation.
Standardization	Evaluated as medium. Data lakes are standardized, and processes for harvesting data lakes are described.
Availability	Evaluated as medium to high. Some of the data processing is manual, however easy and standardized.
Accessibility	Evaluated as high. Information is likely generated by the main user who also organizes the data collection and analytics.
Flexibility	Evaluated as medium. The practice is adaptable to new user requests, however some of the processes of data conversion requires insight and time.
Traceability	Evaluated as high. There is a clear link from the graphical output down to the data source. This is very transparent.

DISCUSSION

The main contribution of this study is the adaptation of the widespread WS technique, named LBWS. This new adaptation can be seen as a VM practice combined with digital technologies. As pointed out by (Tezel & Aziz, 2017), the combination of VM and ICT contributes to an increase in the degree of automation in project control, increasing efficiency in data collection and processing, and reducing the feedback time.

LBWS has also been assessed in relation to requirements of VM with focus on digital VM practices (Pedó et al., 2022). Overall, it is assessed that most of the requirements, to a high degree, are fulfilled in LBWS. As the development of LBWS as a VM practice is still ongoing, the next paragraph will discuss future steps, particularly how LBWS can be implemented and integrated into daily managerial routines and processes.

Implementing VM in construction projects poses additional challenges in comparison to manufacturing due to the complex and project-based nature of construction (Valente et al., 2019). In construction, VM should increase the involvement of workers in continuous improvement efforts (Bernstein, 2012) because it allows for rapid understanding of and response to problems (Bateman et al., 2016). Valente et al. (2019) advise a 4-step model for devising digital VM practices for production management in construction. The first step is an observation phase, where the problem itself is investigated. This step has already been documented for LBWS, cf., the DSR cycle. The second step is to identify the user and user needs to identify the level of visual literacy, which information is required, types of data, etc. The user needs have partially been described in the results of LBWS, showcasing four different functions the practice can offer. However, a future step would be to conduct focus group workshops with industrial experts to elaborate further on user needs. This focus group workshop would also be useful for the fourth and final step, namely defining the final visual attributes. These four steps to implement a digital VM practice complies with the VM typology presented by Brandalise et al. (2022). The final level in their typology is the integration into daily managerial routines. This needs to be further formalized for LBWS, as it currently offers a number of functions, i.e., visual information analysis types, that can be used to identify problems and potentials of the production system.

CONCLUSION

The LBWS is, to the authors' knowledge, one of the first adaptations of the WS technique with ICT application. It brings together the workers' distribution of time into work activities, as the traditional technique, and the geographical location of the WS observations. It presents visual information, i.e., WS data on a map or site layout drawing. Four different types of information and analysis useful for project and site management have been showcased. For this presentation purpose, data from a case study was applied. Although different data like WS categories and location data were collected, the duration of the field tests and the depth of integration in company information systems are insufficient to provide conclusive results of the utility of LBWS.

The utility was assessed by evaluating LBWS with respect to six requirements of digital VM. Overall, the assessment was positive, however, it was recognized that additional implementation steps are needed, in particular with respect to further analyzing user needs and how to integrate into process routines. Several recommendations were made for improving the tool, among them to conduct focus group workshops with industrial experts. While the results are positive and indicate the value of LBWS-enabled process control, further development and testing are needed.

Another significant limitation of the tools is the manual data collection process, which can be laborious and error-prone. Moreover, the accuracy of the locations of the workers collected from the photos could have impacted the results. Other tools for gathering workers' coordinates (e.g., GPS trackers) should be tested in future studies. Lastly, the tool provides delayed information, not contributing to conducting real-time analysis.

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ANALYSING THE VALUE ADDING ACTIVITIES IN THE BRAZILIAN CONSTRUCTION COMPANIES

Lucas B. Bizarro[1], Luís C. Staudt[2], Bernardo M. B. S. Etges[3], and Marcus C. T. Fireman[4]

ABSTRACT

This paper presents an update of a study carried out by Etges (2018) in which an approach to answer the question about the level of value adding activities in Brazilian companies is presented. Taking into consideration the concepts of Lean Construction, adding value and wastes, and Value Stream Mapping (VSM) allied to the perspective of Operational Excellence, the study was conducted in 26 different companies divided into 7 categories of construction works, namely: airports, buildings, renewable energies, highways, Intracity, pipelines and railways.

The analysis of the methodology consisted of characterizing the concepts of wastes and of the Value Stream of processes, and this was added to field analyses using the Work Sampling Method (WSM), which consists of measuring and identifying the level of wastage and adding value to the operation at the place of execution. The results show a low level of activities that add value in the sectors analyzed, representing, in the general analysis, 28% of the total time in manhours available. The results are also categorized by the predominant wastes in each category of construction works, and, in the general analysis, 48% of the wastes are related to Waiting.

This analysis makes it possible to identify great opportunities for reducing waste and it is extremely important for the construction industry to promote critical actions aimed at leaner construction management.

KEY-WORDS

Lean Construction, Value-adding activities, Value Stream Mapping, Work Sampling Method.

INTRODUCTION

One of the main problems of the construction industry is the lack of improvement in its productivity over time (Abdel-Wahab and Vogl, 2011; Fulford and Standing, 2014). The study carried out by Barbosa et al (2017) identified that in the last two decades, the growth rate in productivity in the construction industry was only 1%, a figure well below the average of the world economy, which is 2.8%, and almost 4 times smaller when compared to industries such as manufacturing. The reflection of low productivity can also be identified in the most recent

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study presented by the Brazilian Chamber of the Construction Industry (CBIC, 2022), which pointed out that 45% of projects exceed budget and 27% are completed after the expected deadline.

In this context, one of the alternatives that companies have adopted are the principles and concepts of Lean philosophy (Fabro et al., 2020). Coming from the automotive sector, Lean strengthens the culture of continuous improvement in companies by systematically reducing losses and waste (Shinohara, 1988; Pheng et al., 2016; Salgin, 2016). Under the lens of Lean, companies in the construction sector are starting to see the everyday existence of activities that do not add value and that result in low productivity. Such activities consume resources, time or space and do not add value to the product (Neve et al., 2020).

Hence, the use of concepts and tools that help the construction industry to reduce this waste is of fundamental importance for the survival of companies in the sector and for the conservation of the vast quantity of material resources consumed by the construction industry (Cardoso et al., 2005). This search by the construction industry to improve its productivity has been identified by Etges (2018), and this paper sets out to update the work already carried out. Still according to Etges (2018), to understand the level of value adding activities on the sites under study, three main concepts need to be integrated, namely: waste identification, value stream mapping and Gemba routines. In the latter, the Work Sampling Method (WSM) will be applied to enable the volume of activities that add value and their wastes to be monitored.

This study aims to update the analysis carried out by Etges (2018) by identifying opportunities and create a reference to allow academics ans professionals in the sector to be aware of the amount of waste in the sector, allowing insights to improve productivity in the construction industry. Thus, this diagnosis aims to illustrate the state of added value in construction industry during execution of activities based on using value stream mapping and observing wastes by using Gemba. Analyses were undertaken in 26 Brazilian companies in two specific periods, between 2013 to 2016 which was carried out by Etges (2018) and the second period between 2018 to 2022 which aims to update the analyzes in the first study.

The article is divided into three phases. The first phase consists of exploring the conceptual references in the literature on adding value, wastes, value chain and value stream mapping, and on how to identify value by seeking to understand the production process. The second stage will address the methodology used to identify activities that add value to the production process and, finally, the results and discussions of the analyses will be presented.

REVIEW OF THE LITERATURE

This section will address the literary review of the three main concepts and tools used to build this paper. They are: (a) definitions of activities that add value and waste; (b) Value Stream Mapping and (c) the Work Sampling Method.

VALUE-ADDING ACTIVITIES AND WASTES

The activities within a production process can be classified as follows according to Hines and Taylor (2000): Activities that add value, these being the activities that make the product or service more valuable to the customer; Necessary activities that do not add value are activities that the customer does not consider valuable but which are necessary; and finally, Activities that do not add value, which are activities that are not valuable to the customer and are not necessary in the current circumstances (Pothen and Ramalingam, 2018). Koskela (1992) also argued that activities that do not add value have three main causes, namely: design, ignorance and the intrinsic nature of production. This definition is in line with the discussion proposed by Koskela et al, (2013) in which the seven classic wastes are in fact in a specific context and that, for the construction context, the crucial wastes must be identified and defined from the characteristics of this type of production. Koskela (2000) defined that in order to apply these concepts in civil construction, what must be understood is what the main wastes to be eliminated in construction are. Thus, the seven wastes defined by Ohno (1988) are: excess production, time on hand, transportation of products, processing itself, stock on hand, motion and the manufacture of defective products.

In this scenario, to analyze the list of construction-related wastes, three main requirements stand out, namely: the list of wastes must be conceptually compatible with the construction industry, empirically justified, i.e., the focus is on the most relevant wastes, and is persuasive and motivating for improvement actions (Koskela et al., 2013). For this reason, Value Stream Mapping is a key tool for understanding wastes in each project, considering the seven losses being considered as possible references.

It is sought to increase the share of work that adds value by eliminating wastes, thereby progressively reducing activities that do not add value (Ghinato, 1996). Thus, the complete understanding of the production process is fundamental for identifying what to eliminate, since, very often, the activities that do not add value are not easily visible. Hence, opportunities to reduce these losses and real improvements arise (Ohno, 1997).

VALUE STREAM MAPPING (VSM)

According to Womack (2004) value stream mapping is the identification of all specific activities that occur along a flow referring to a product or family of products. It is a simple but effective approach to understanding the flow of material and information as value is added to a product or service throughout its processing (Slack, 2002). Thus, to map the value stream, the production trail from the beginning to the end of the process, from the consumer to the supplier, and then a map of the current state of its material and information flows should be drawn up. Following on from this, one should draw up the map of the future state of how its value should flow, and thereby improve the current flows (Rother and Shook, 1999; Rentes et al., 2004).

By doing so, the main function of the VSM becomes to identify when and where the value starts to be triggered and where there is waste, since the team members become more objective in eliminating losses with the use of this tool (Menezes, 2003; Tapping et al., 2002). Recently, new studies, such as Covarrubias et al (2016), have been carried out focusing on the construction industry, in which VSM was used to improve administrative processes in construction. Another study demonstrated that the use of VSM and the Work Sampling Method are two important tools for the Lean philosophy, which have the objective of reducing and minimizing waste in the life cycle of a process and, consequently, of increasing productivity (Pothen and Ramalingam, 2018).

WORK SAMPLING METHOD (WSM)

One of the ways to monitor the number of activities that do not add value which are performed by laborers is to apply the Work Sampling Method. This method, initially applied in industry by the British engineer Leonardo Tippett in 1927, aimed to observe and quantify the time spent on different tasks in order to deeply understand the factors that increase or decrease their efficiency (Neve et al., 2020). Introduced in the civil construction sector around the 60s (Thomas and Guevara, 1984), the tool has enabled the effectiveness of using manual labor to be measured, thereby indicating the portion of time allocated to non-productive activities and exposing the soundness of the planning of the work fronts.

The WSM consists of making a series of snapshot observations, such as photos, of work in progress over a period of time to measure workers' productivity (Jenkins and Orth, 2003). This method, therefore, enables moments of low productivity to be identified, which in turn, can generate enough information to carry out the necessary corrective actions (Thomas and Napolitan, 1999). Despite criticisms regarding the reliability of the method, Wandahl et al (2022) monitored data through nine days of continuous WSM application considering Direct Work, Indirect Work and Wastes. They concluded that the WS Method is robust, considering the three types of testing involved in the Research (Wandahl et al., 2022; SALLING et al., 2022).

A study conducted by Perez et al (2015) used the WSM to measure the amount of productive and non-productive work regarding transport waste in physical flows of construction processes, and thus demonstrated activities that are necessary, avoidable and unnecessary. Another study carried out by Pothen & Ramalingam (2018) obtained positive results when using the VSM tools and the WSM to understand the current productivity scenario in a construction project and to identify and reduce the non-productive time spent by workers, thereby increasing the productivity of the process. Recently, digitization has been used as a way to capture samples of workers' behavior and the respective value adding activities. Perez et al. (2022) added the geographic location for each WSM observation in order to be able to better understand the workers' behavior when carrying out their activities, thus analyzing, jointly, the workplace.

METHODOLOGY

With the objective of supporting the understanding of the productivity scenario in civil construction in Brazil, this research carried out by a consulting company applied the WSM in two different periods, from 2013 to 2016 and from 2018 to February 2022. Data were collected in 26 different companies divided into 7 categories of construction works, namely: airports, buildings, renewable energies, highways, Intracity, pipelines and railways. The activities in each category was selected based in two criteria, (a) the activities that was in execution during the construction on VSM current state; and (b) activities that was identify as bottlenecks during the construction routines.

The WSM was used to measure the number of activities that add value and activities that do not add value (Perez et al., 2015). The traditional definition for adding value to activities set by Koskela (1992) states that activities that add value are activities that transform materials or information into what is requested by the customer; Activities that do not add value, also called waste(s), can be considered as activities that consume time, resources or space, but do not add value.

Applying the WSM in the present research consisted of direct observations and data collection construction sites. The laborers acting in a certain activity were the object of analysis. At each fraction of time, (approximately 5 min), a sample of the work was analyzed and the activities that the laborers performed were classified into macro categories in accordance with Hines and Taylor (2000) which is represented in Table 1.

Table 1: Macro classification of the activities

Category	Description	Value Category
Value-adding activities	Activities which transform material or information into what the client is looking for	Adds value
Activities with hidden wastes	Activities which do not add value, but are necessary to support activities that add value (e.g., motion, transport)	Auxiliary
Activities with evident wastes	When the activity does not add value (e.g., waiting, rework, etc.)	Does not add value

The macro classification of activities facilitates the visualization of process inefficiencies, thus enabling an understanding of the potential for reducing waste in the system. In order to better understand waste, during each analysis, the activities performed by the laborers were classified into 11 subcategories that enabled the work to be understood. This classification was based on the definitions of Ohno (1988) and these are represented in Table 2.

Table 2: Classification of wastes

Category	Description	Value category
Area	When the excessive use of area occurs	Does not add value
Delays	When a time challenge occurs in carrying out the activity	Does not add value
Loading and Unloading	When the need to load and unload materials occurs	Auxiliary
Defects/ Rework	When production errors occur resulting in the need for repairs	Does not add value
Waiting	When the work front is paralyzed and the worker is kept waiting	Does not add value
Inventory	When the presence of materials and products in excess occurs in the production chain or in the storage areas	Does not add value
Excess production	When processing occurs beyond that requested by the client	Does not add value
Motion	When the employee needs to undertake more movements and displacements to carry out the activity	Does not add value
Preparation	When preparing to conduct the activity occurs	Auxiliary
Quality	When the conduct of the activities is checked	Auxiliary
Transport	When the materials or products are moved	Auxiliary

RESULTS

The data presented in this study correspond to the collection of 4374 samples, totaling more than 218 hours of observation. The analyses were collected by consultants and the general public, trained by specialists. The collection time in each macro category of work is detailed in Figure 1.

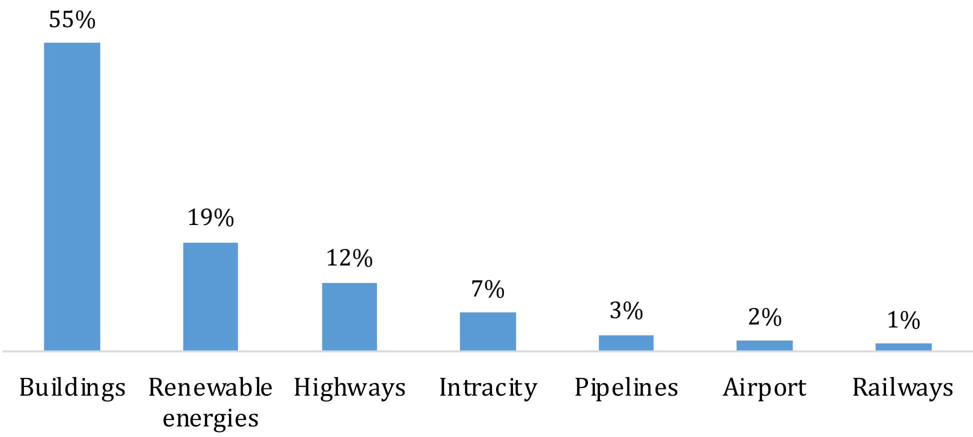

Figure 1: Collection time by category of construction work

From the data collected and analyses carried out under the WSM, a significant level of 72% of the efforts of manual labor dedicated to activities with some type of waste was identified. That is, of the 218 hours of work analyzed, transformation processes that add value to the customer were occurring in only 28% of this time. The results presented below show the relationship between the activities that add value and the wastes observed in civil construction, related to auxiliary activities (hidden waste) and activities that do not add value (evident waste) to the product. Figure 2 presents the absolute data referring to the addition of value in the activities carried out by the laborers.

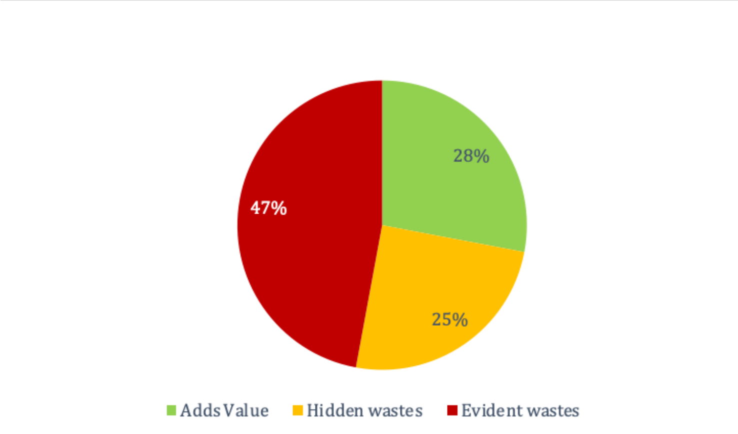

Figure 2: Analysis of added value

On stratifying the results obtained in the main civil construction segments, we can observe that the best results in terms of value adding activities are linked to works with high repetitiveness, as is the case of railways (37%) and buildings (34%) (Figure 3). In the case of buildings, this category of work was the one with the lowest percentage of activities that did not add value (30%). Even considering that building construction have high variety of typologies, one may say that the repetitiveness and flow of activities is objective for a more productivity performance, which is associated with a more consolidated construction system, in which the composition of teams and the division of tasks are mostly standardized.

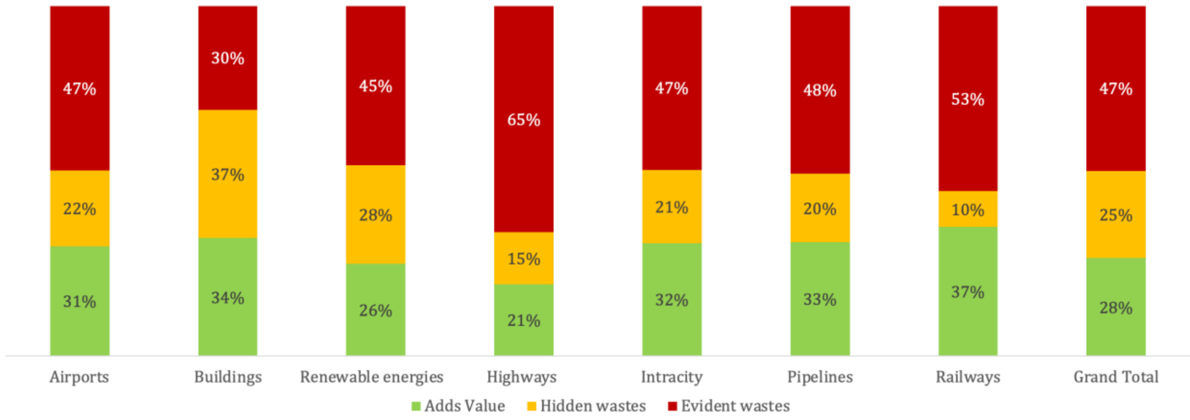

Figure 3: Analysis of value adding activities by type of construction works

On the other hand, the segments of Renewable Energies and Highways presented a lower value adding activities (26% and 21%). The two segments have the following characteristics in common: (a) long longitudinal distances that demand efficient planning and logistics; (b) characteristic complexity related to relief and vegetation; (c) strong dependence on heavy equipment that requires more attention to response time for maintenance.

TYPES OF WASTE

From the work sample analyzed, the types of waste that make up each activity were mapped and it was identified that three categories represents the major wastes: Waiting – 48%; Transport/Motion 19%; and Preparation – 18%, which are represented in Figure 4.

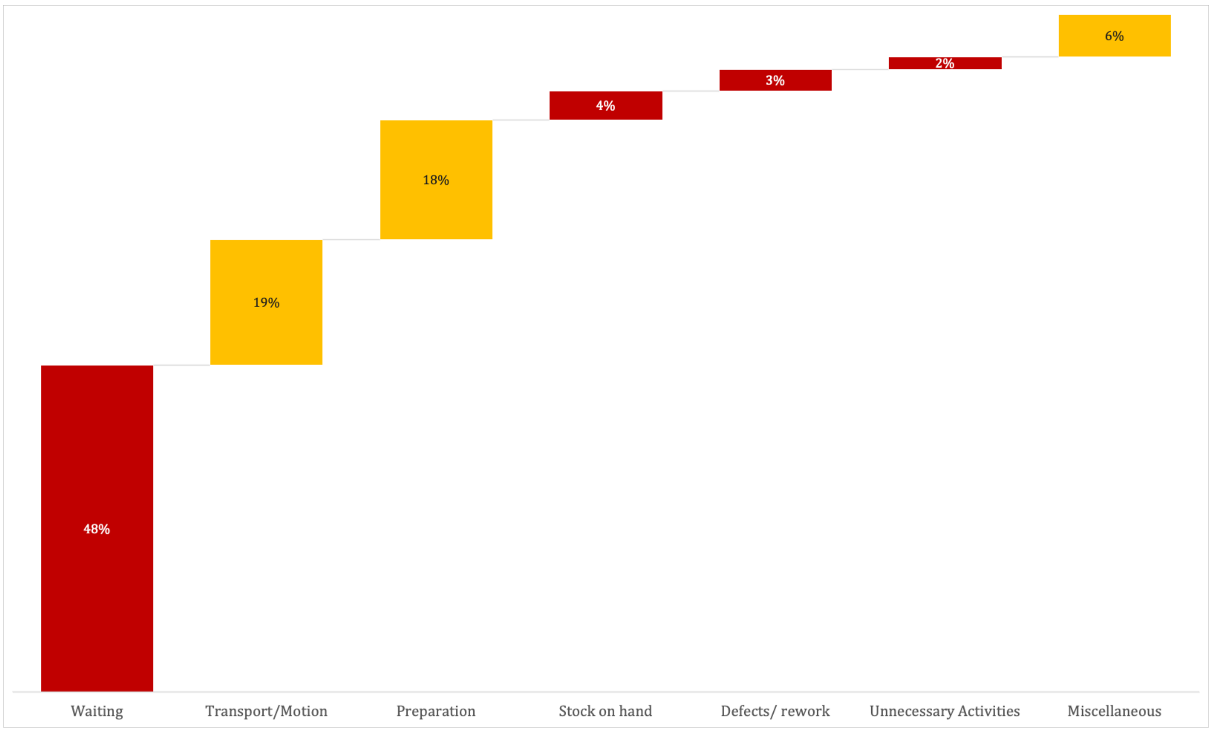

Figure 4: Percentage of wastes per category

Waiting (48%) was the mains waste identified, often perceived in civil construction due to idle workers, waiting on a availability of materials, equipment or even information. This can be reduced by adopting an assertive planning of the work stages, aiming to predict which materials and equipment will be needed in each work stage and ensure that they are available at the right time. In addition, constant monitoring of the production process is essential to identify problems and bottlenecks in production and to be able to act quickly and agilely in solving problems. The use of lean routines and tools, such as the Last Planner System, significantly reduced this waste and led to more efficient work management.

Transport and handling waste (18%) can be reduced with efficient logistical planning in civil construction. For this, collaboration between work sectors, especially between planning and logistics teams, is essential to ensure efficiency. The definition of routes and routines must also be guaranteed in order to minimize excessive movement and transport at peak times and minimize the distances traveled by employees and materials. In addition, the adoption of tracking systems can help control and monitor equipment and work materials, allowing managers to identify bottlenecks and opportunities for improvement.

Another important set of data shown in Figure 4 is the number of defects/reworks in the sector, which corresponds to 3% of the waste analyzed. Despite the low number, given the reality of the sector, it is important to make it clear that the analyses were mostly carried out under the main execution of the services, i.e., the traditional reworks or repairs that are normally carried out in a more advanced phase of the projects were not contemplated in the analysis.

Performing a focal analysis on the three types of construction work with the highest volume of samples collected (Buildings, Renewable Energy and Road), what can be identified is that the three main wastes are the same. They only differ in proportion (Figure 5):

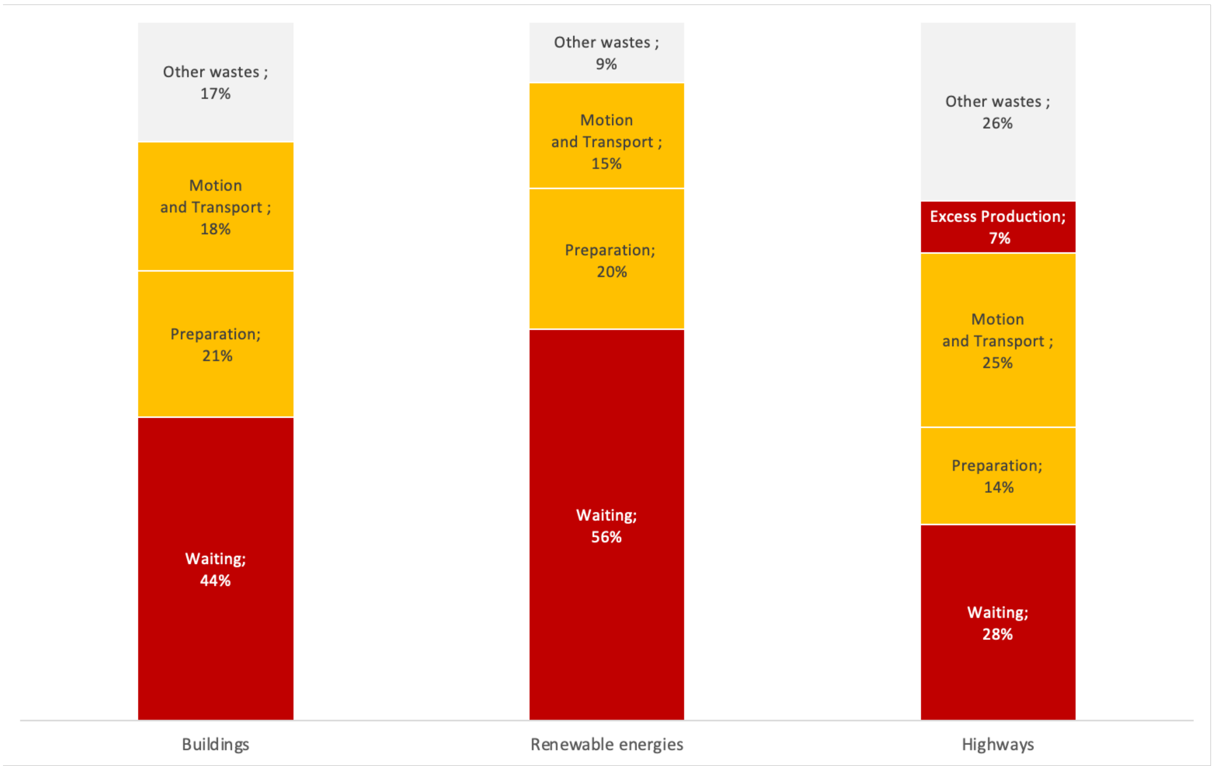

Figure 5: Percentage of wastes by category

Analyzing the proportion of waste presented in each sector, it is possible to infer that:

- The building sector has characteristics that allow greater efficiency (reduced size of construction sites, standardization of the product such as houses or building floors, greater specialization of manual labor) in relation to other types of works. However, it presented a high percentage of waiting (44%) and of motion and transport (18%) in the observations due to factors such as sharing logistics equipment (elevator rack, manipulator), poor sizing of auxiliary teams (laborers) or even errors in the distribution of activities between teams.

- In the Renewable Energies sector, we highlight as reasons for 56% waiting, the high frequency of moments of teams being idle at workstations waiting for formal clearance to start activities, such as: work safety clearance, clearance to work in a given environment, clearances from the previous work front.
- In the highways sector, we draw attention to the waste of excess production (7%), which was sometimes noticed due to the fragility of the control of executing the service. For this reason, the work carried out on the road section is greater than what would be necessary - for example in a base or sub-base compaction, or in precast production centers used in the construction of highways, which can lead to wasted resources and increased costs. In short, due to the difficulties of following up on execution, excess becomes the default. In addition, Transport and Motion (25%) also have great opportunities for reduction, commonly caused by lack of material delivery schedule, excessive stock of materials, difficulties in accessing roads with remote areas and excessive movement of materials due to lack of organization on construction site. To reduce this waste, the adoption of collaboration and visual management tools through the Last Planner System practices is an efficient alternative to reduce these problems, in addition, the use of technologies such as drones and monitoring systems, it can help to optimize the production process, allowing a more efficient management of resources and a reduction significant waste.

DISCUSSION AND CONCLUSIONS

By determining the current status of companies in the construction industry regarding adding value to their processes, it can be stated that the study achieved its objective. The study also enabled the construction companies, by using tools, to perceive the possibilities and needs for improvements applicable to their respective processes. The samples analyzed demonstrate that the Work Sampling Method was an efficient tool for identifying value-adding activities in construction projects.

The results analyzed in this study showed that 72% of the construction activities observed do not add value to the process, a slightly better number compared to Etges (2018) who presented 74% of time spent on wasteful activities. Recognizing these data is of paramount importance for the construction industry to promote critical actions aimed at improving performance, reducing waste and costs, and mainly, achieving leaner construction management. Experiences similar to those of Thomas et al. (1991) were perceived. They suggested that the results can stimulate discussions between managers and, in this way, serve as support to stimulate the search for improvement. Analyses are fundamental to demonstrate to managers the time spent on activities that do not add value.

The building sector has shown great opportunities for reducing waiting and movement and transport waste. In view of this, implementing practices that optimize performance related to layout improvement, in terms of reducing waste, improving the movement of material, storage organization and the use of technology, such as BIM-4D for planning layouts and work phases, can facilitate and reduce losses in the operation, which are fundamental for companies to obtain a competitive advantage in the current scenario.

The logistical issue is also essential to reduce waiting and wastes in movement and transportation in works that have long distances to be covered, such as road works, wind farm works, transmission lines works and photovoltaic plants. In these cases, the supply of materials is one of the issues that can be taken into account in terms of travel time. In road works, intermediate points for stocking equipment and materials can be considered. In addition, using technologies such as digital systems to control their equipment can help companies to carry out a more robust data analysis in order to eliminate this waste.

Due to the large number of companies that were analyzed, one of the limitations of the work is the availability of access to customer data, therefore, as suggestions for future work, it is interesting to analyze it by type of activities. Besides, it would be interesting to apply improvements in a process and to compare value adding activities after implementation. Case studies applying technological solutions aimed at reducing waste in an infrastructure company can help make it more competitive, which can contribute to the answer of the question: how many infrastructure companies use a real sampling of their equipment?

Furthermore, it would be interesting to expand the data sample and increase the number of projects analyzed. Different regions, branches of construction, with different types of technology can be relevant for the comparison between sectors and projects aiming at the continuous improvement of the industry. The main gain from the study was the perception that the Brazilian construction industry is susceptible to changes and that this is fundamental for building a more competitive and efficient sector.

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ACHIEVING A 4-HOUR TAKT TIME – AND DRIVING CHANGE WITH IT

Jaakko Riekki[1], Jukka Rannisto[2], Joonas Lehtovaara[3], Olli Seppänen[4], and Antti Peltokorpi[5]

ABSTRACT

This study seeks to validate the hypothesis that takt production can be used as a driver for implementing several lean construction concepts together and for making them work as a system. This is done by studying a single case project where takt production with a 4-hour takt time was a core element of the operating system. In studying the case, a set of lean construction concepts found present in the project are extracted and analysed. It is concluded that takt production and in particular the short takt time worked to integrate the stakeholders and enabled the individual lean construction concepts to work in a tight relationship. Future case studies could be more explicitly designed to further validate the hypothesis.

KEYWORDS

takt production, daily management, logistics, continuous improvement, collaboration

INTRODUCTION

According to Koskela et al. (2002) in their description of a Lean Project Delivery System (LPDS) there are two differing interpretations of lean construction: (1) application of lean production methods to construction and (2) a new theory-based methodology for construction that draws inspiration from lean production. In practice the approach of the first interpretation has demonstrated good results yet advancing towards the second would be desirable.

As methodologies akin to the second interpretation, we have The Last Planner System (LPS) (Ballard & Tommelein 2021) that is an important component of lean construction and has gained wide acceptance, and the Location-Based Management System (LBMS) (Kenley & Seppänen 2009) that attempted to bring construction planning together with design scheduling, procurement planning and production control. These systems however have not yet been able to bring to practice the transition from lean construction as a kit of methods to a holistic theory-based system. On the other hand, applications of lean production methods have demonstrated performance gains in individual case projects but there seems to be a knowledge threshold at the point where we are looking for ground up methods that can be used as the underlying drivers

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from a set of separated elements towards a system of interrelated concepts. By ground up we mean that it can be applied in practice even in the absence of a theory-based methodology.

Takt production has been suggested as one such underlying driver. Lehtovaara et al. (2020) developed a maturity level model that describes how the development of an organization's takt production capability can be used to connect and implement many other lean construction concepts. Peltokorpi et al. (2021) identified takt production as one key driver for systemic change and suggested a conceptual framework of integrating a set of sub-systems present in construction, that need to be developed together in order to achieve sustainable development. From a more single project-based viewpoint Tommelein & Emdanat (2022) described takt planning as an enabler for bringing together and as a starting point for continuous improvement using lean principles. Studies involving takt production have also highlighted the need to connect with other lean production concepts. For example, Lehtovaara et al. (2021) presented how takt production contributes to construction production flow but with the requirement of significantly increased effort in terms of planning, control and continuous improvement.

Building on this idea we suggest that one way of gaining more knowledge about how to make progress in the transition from applying a set of tools towards applying a management system is to study a successful takt production case project where a scattered set of other lean construction concepts were identified, analyse the effects of the individual efforts, look at how they worked together and, specifically, how they related to the takt. By doing this we can seek to validate or refute the hypothesis that takt production can function as a ground up driver towards a more holistic approach for future lean construction implementation. To this end, this study aims to explore a case project where a short takt time of four hours is highlighted as a novel concept for driving production flow and where many other lean construction concepts were found to be present.

Among these concepts are collaboration, as argued useful by Koskela (2022), integration of design and procurement, an interesting avenue for furthering collaboration as explored for example by Uusitalo et al. (2019), and the core lean principle of continuous improvement. Top management support is required because an implementation of lean tools and methods by themselves often leads to failure without a cultural change in the organization (Walter et al. 2020). Similarly, Hackler et al. (2019) shares efforts towards developing lean leadership and disseminating lean through a larger scale training program. These views are supported by a questionnaire sent out to LCI members that propose barriers for lean implementation (Demirkesen et al. 2019). Emphasis on planning effort is another common lean production idea and has been demonstrated as a rewarding experience for example by Ghio et al. (1997).

Binninger et al. (2018a) showed the power of small batch-sizes, which came together with intensive daily management and the idea of andon pulls i.e., to stop to fix problems as they arise. Also, relating specifically to takt production, several control adjustment mechanisms have been compiled (Binninger et al. 2017) and the daily management activities of construction managers have been analysed (Binninger et al. 2018b).

Tetik et al. (2019) describe industrialized logistics to better serve the needs of construction. Visual management has as well been experimented with on construction sites with promising results for example by Grönvall et al. (2021). First-run studies (Ballard & Tommelein 2021) may also be considered. Digitalization (Sacks et al. 2020) is a tool that opens possibilities for implementing many of the other lean concepts.

In the next section, the method of analysis of this study is described, including a brief summary of the project general information. After that, the findings of the analysis are presented, and finally, implications of the study are discussed.

METHOD

In the following, we first explain the method of this study and then give a brief general description of the case project and how it was managed.

STUDY METHOD

Because we examine a single interesting project noticed by the authors, the method used is a single case study. We gathered data from the project by gaining access to the project databases and conducting interviews. We then searched the data to extract a set of lean construction concepts evident in the project. After that we analyzed how the concepts worked in the project and finally, we report on the findings of the analysis.

The data used in the study consisted of

- documents such as schedules, production plans, process descriptions, contracts, project presentations, photographs and design documents,
- digital data platforms that were used for process planning (Miro), quality control and issue tracking (Congrid) and material management (NPL),
- 4d video animations that were created to visualize the takt phase,
- unstructured interviews with the project participants who were involved in planning, managing and leading the project and
- site observations by the first two authors that consisted of general site walks, site personnel interviews on the spot and included observation of the daily huddles.

The extraction of the concepts to be analysed was achieved through discussions between the authors that followed a preparation made by the first author's study of the data. It was noted that the set of concepts could be grouped and renamed in many ways, but the aim was to settle on a set that is representative of what was learned from the data, does not have excessive overlap between the concepts and would look familiar to most lean construction professionals.

An analysis on how the concepts were used, what, if any, were their benefits or drawbacks and what could be concluded from the experience of implementing them was carried out by asking the following questions for each of the identified concepts:

- (Q1) How were the lean and takt concepts present in the case project?
- (Q2) What were the apparent benefits or drawbacks in implementing the concepts?
- (Q3) What can be concluded from the experience of having implemented the concept?

The answers to these questions and their data sources are presented in the findings section. A deeper reflection on the analysis and the research hypothesis is presented in the discussion section.

CASE PROJECT DESCRIPTION

The case was a renovation project where an office building was turned into a hotel. The site's location was a crowded city center with limited space, posing a challenge for logistics. The building was constructed in several phases from 1920 to 1952 and had since been transformed through other renovation and new construction projects. Through these transformations the building has a varied history of use from industrial to office before being turned into a hotel.

The project consisted of around 29 000 gross m^2 which included 352 hotel rooms with their corridors and other hotel facilities such as restaurants, spas, reception areas and technical spaces. The project started in January 2020 with the demolition phase and was finished and handed over to the client in June 2022.

The construction of the hotel rooms and corridors starting from interior walls were managed by takt production while the other construction phases were managed by a combination of

LBMS flowlines and a modification of the Last Planner System. We will call the phase of production where takt production was used the *takt phase* which is also the focus of this study. Separated from the takt phase, a preparation phase of demolition, structural changes, concrete casting and floor levelling was managed by the other means before the takt phase started. The takt phase started in January 2021 and was finished in April 2022, with total duration of about 16 months.

The project was managed by a project management organization (PMO) who was involved early in the project by the client from goal setting to design process management, procurement preparation and finally to being responsible for the construction site management. In the construction phase the PMO was responsible for the planning and coordination of operations including design, the trade partners and the logistics. However, the designers, trade partners and the logistics contractor were in direct contractual relationship with the project client as part contractors and not with the PMO, who acted only as a project management consultant and a supervisor. By the PMO's requirement, the part contracts of the trade partners were included with a takt appendix that described the takt principles to be used in the takt phase and required the trade partners to take part in takt planning, daily huddles during the takt phase, preparation of work in the takt plan and quality assurance of the finished takt areas.

In the project management role, the PMO took strong leadership in planning, facilitating collaboration and implementing several lean construction concepts in the project. Specifically, the enforcement of takt production was due to the PMO's leadership.

The project was described as successful by the PMO and the client from the schedule point of view. The PMO also reported that in their view specifically the use of takt production in this project eliminated several sources of waste compared to both the other phases of the same project and other similar projects without takt production.

FINDINGS

Figure 1 depicts the set of lean construction concepts that were found present in the case project arranged into four groups. The concepts to be analysed by answering the three questions are in the white boxes.

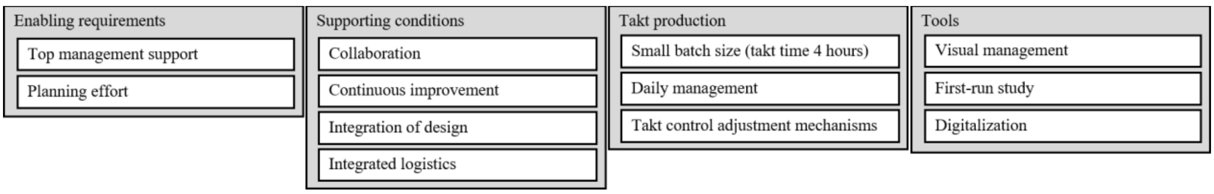

Figure 1: Lean construction concepts found in the case project arranged into groups.

Top management support: The site visits and interviews indicate that the top management of the PMO at the site put a lot of pressure on the management team, the logistics operator and the trade partners to make efforts in new ways of working along the lines of lean construction concepts. The highest-ranking manager at the site had knowledge and experience about lean construction concepts and made efforts to put them into practice through frequent coaching of the management team. In addition to putting pressure, the top management expressed an explicit recognition of the need to allocate an uncommonly high number of resources to the planning phase in order to enable a thorough preparation. (Q1)

These observations make clear the benefit that most of the lean efforts would not have been realized without the pressure and commitment from the top management. There was however no formal lean leadership initiative present, and some members of the management team were observed in a few situations as having been somewhat at a loss in the middle of several new methods pushed by the leadership all at once. (Q2) This was taken to be evidence for the proposition that, in addition to support from top management, getting a good grasp of lean construction concepts requires proper training and coaching. (Q3)

Planning effort: As hinted above, the planning documents and interviews indicate that an exceptional effort was put in planning the takt phase from early on. Evidence of this was also an initial two-day workshop with a large group of the PMO company's production management staff, that began identifying the work steps in the production process along with their quantities and performance rates. This workshop was held around six months before starting production, was led by an external consultant and acted simultaneously as a training session for the participants into takt production principles. In the workshop the knowledge base of around 15 experienced construction professionals was leveraged to gain insights into the details of the production process. Afterwards a group of 2-4 people was assigned to develop the plan further. Around three months prior to the start of the takt phase, two core members of the group worked full-time in fine-tuning the plan. Similarly, around six months before production start, the logistics contractor was tasked with defining the supporting material management processes required by the takt plan. The materials required by the takt work packages were quantified in detail and the methods of transportation as well as lay-down areas on site was planned for each type of material. Closer to production, a preparation meeting was held with each trade partner where a short training of takt principles was given and their input into the takt plan's details and feasibility was solicited. (Q1)

According to the interviews the production management team along with the logistics contractor gained benefits from the planning effort by being well versed in the plan ahead of production which gave them confidence in controlling the takt phase and dealing with the trade partners. Good understanding of the required material and worker resources enabled the production management to tackle surfaced problems quickly by being able to refer to the already gained knowledge. In short, the interviews indicate the sentiment of the management team that putting this exceptional effort in planning and preparation helped in creating and controlling a good production process. (Q2)

It is difficult to discern the economic impact of the decision on the amount of planning and preparation. The case project can however be taken as anecdotal evidence for the hypothesis that the line after which more effort on planning does not gain a net benefit anymore has not yet been reached. It should also be noted that the management team of the takt phase had no prior experience or knowledge of takt production. The careful preparation was used simultaneously as a training opportunity. (Q3)

Small batch size (takt time 4 hours): From the schedules and planning documents it can be seen that the takt plan was built around the smallest space unit of one hotel room and a corresponding length of corridors as the takt areas, which eventually led to decision on using a takt time of four hours i.e., a half workday. This is illustrated in an excerpt of the takt plan and progress record in Figure 2. The interviews reveal that the target for a short takt time was set early in the planning phase explicitly because of the perceived benefits of a small batch size. During the planning process the target was deemed feasible and incorporated into the plan. (Q1)

As told in the interviews, the short takt time enabled a lot of flexibility in the work step definition, sequencing, buffer management as well as levelled the material flow and drove the tight control efforts during production. As evidenced by the schedules, planning documents and progress records, planning and controlling with a short takt time also made the required work steps and progress tracking highly visible and accurate. The feasibility of controlling such a short takt time was said in the interviews to have been initially questioned due to the perceived increased management burden. However, the short takt time was later not only proven feasible but indeed regarded as the key driver for success. (Q2)

Through interviews it was clear that the management team felt that the burden increased by the short takt time was set off and well paid back by the tightness, flexibility and accuracy of control. These observations are similar to what Binninger et al. (2018b) described in their experiment with a short takt time on a smaller scale project. (Q3)

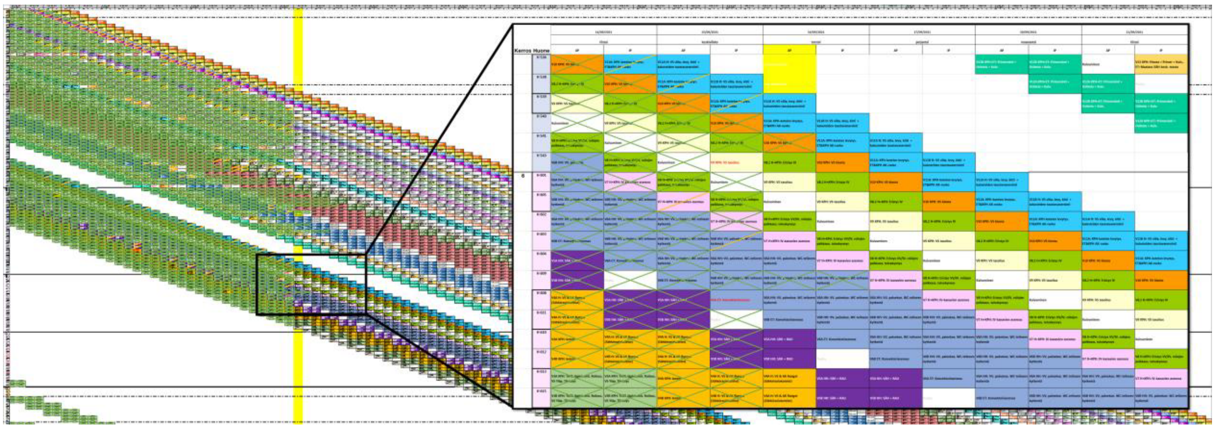

Figure 2: An excerpt of the takt plan and progress record on 16th September 2021 illustrates the plan with a 4-hour takt time. The progress was recorded for every takt in the daily huddles. A green double cross over a wagon stands for done, yellow single cross stands for started but incomplete.

Daily management: The PMO enforced a disciplined daily management process of takt control through worker huddles where all the trade partners were required to be represented every day. In the huddles, observed by the first two authors, the progress in the preceding two takts reported by the trade partners were recorded in a schedule printed out on a large sheet of paper for the purpose of visualization. The progress was simultaneously also recorded in the digital spreadsheet schedule. Figure 3 shows what the daily huddles looked like. Any issues raised during the huddle were also digitally recorded on a separate spreadsheet where in total over 7,000 issues were found having been recorded during the takt phase. Immediately after the huddles, the management team went to solve the surfaced issues with the trade partners. (Q1)

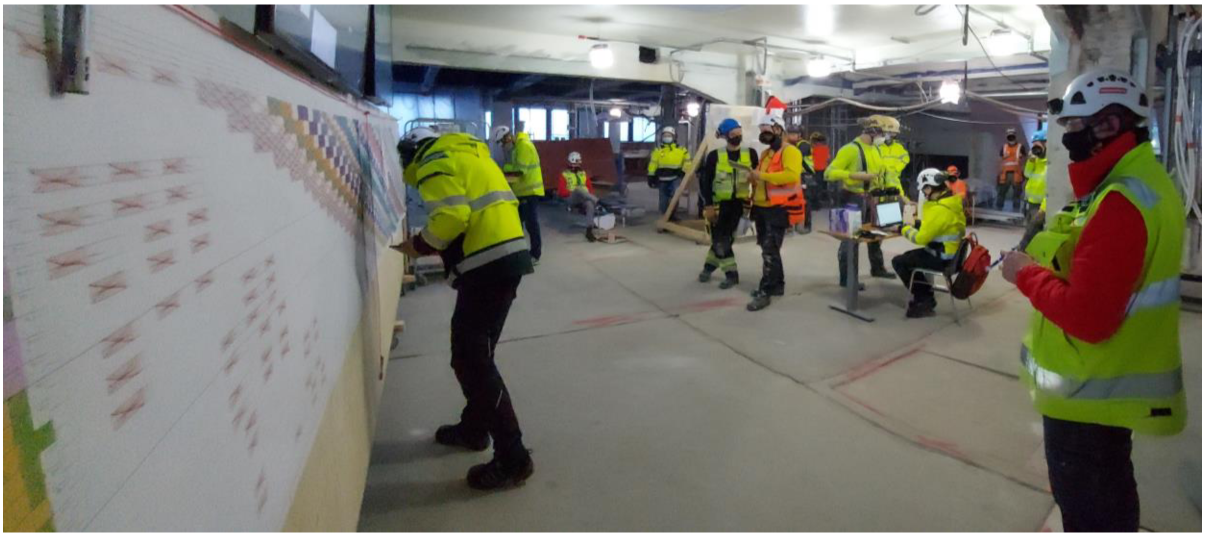

Figure 3: The progress was recorded both digitally and on a visual board in the daily huddles. The raised issues were also recorded in a digital spreadsheet.

The daily huddles served in sharing a common situational awareness of the takt process and enabled the trade partners to get a fast response to issues in their work. At the same time, the progress of planned work was updated and visualized daily. (Q2)

Learned from the interviews, the daily huddles required some enforcement from the PMO. The site observations confirm that some trade partners were reluctant to take part in the huddles, since the huddles took around 30-45 minutes of their workers' time. The PMO held the discipline by referring to the contractual clauses about the huddles. After initial backlash, the huddles became routine and were attended to by almost all trade partners even when they were longer than required in the contract, because they found them useful. After the project was finished, the PMO identified the need to consider breaking the daily huddles apart into several smaller size huddles in order to shorten them in their future projects. (Q3)

Takt control adjustment mechanisms: The studied schedules and interviews reveal that at least the following takt control adjustment mechanisms similar to presented by Binninger et al. (2017) were used during the takt production phase: contents of work steps were modified, the sequence of wagons was changed, new work steps were added, buffer wagons were added and takt areas were omitted in order to protect the train flow. In addition to these the worker resources and material delivery quantities were adjusted as knowledge about their requirements was gained during production. Notably there was one situation where a decision was made to split and stop the trailing part of the train in order to solve problems that had accumulated delays and blockages. The trailing portion of the takt train behind the delayed wagon was stopped for 2 weeks to let the delayed wagon catch up and solve the problem. The leading portion of the train was not affected by the stoppage, and it was kept moving normally. The stoppage time was sufficient for the catchup and the train was restarted with the modifications caused by the stoppage. According to the PMO the decision of stoppage for a specific amount of time was clearly communicated to the affected trade partners, and no major complaints arose. The schedule had enough planned buffer at the end to compensate for the delay caused by the stoppage. (Q1)

Problems that were surfaced during production caused some delays, but the deviations were able to be adjusted for with the major benefit that the plan was kept under control throughout the takt phase. One notable downside to the frequent use of adjustment mechanisms was the effort required to update the modified schedule. The takt plan was drawn on a spreadsheet with a low level of automation and each change took several hours or in some cases even a whole day of work to update and repost on the site. (Q2)

Interviews confirm that the adjustment mechanisms were essential in keeping the takt train flowing. The short takt time along with the upfront effort spent in planning made the takt plan very flexible for adjustments even if they required some effort in replanning. The problem of increased effort required for manual data management can presumably be mitigated by development and adoption of more sophisticated digital tools with a higher level of automation for creating takt schedules. (Q3)

Collaboration: The PMO launched a system of workshops aimed at facilitating collaboration between the site management team, the logistics operator and the trade partners. As described in the interviews, the system was called "three-based-meetings" referring to the usual three stakeholders of the PMO, a trade partner and the logistics operator who all had a stake in most matters relating to the takt phase. In contrast to a prior standard way of sending documents back and forth, the PMO organized workshops together with the other stakeholders where planning and continuous improvement efforts were carried out in collaboration. (Q1)

The top site manager of the PMO described and the management team confirmed an anecdotal example where the planning of materials for a trade partner's work package took several weeks when they first tried it in the documents transfer way and was condensed to a single 1-hour workshop after the launch of the system. (Q2) It was also noted that merely the definition of a process for the purpose of collaboration helped in achieving a collaborative way of working. A high impact was achieved with a small nudge. (Q3)

Integrated logistics: According to the PMO, material flow management was identified early as a key requirement for success in the takt phase because of the small takt areas and the challenges posed by the site's location at a city centre. Study of the planning documents showed that the material quantities were calculated, and a delivery strategy was planned for each work package individually.

The logistics operator used a material management software system to manage all the material flows. The takt schedule was imported to the software, where the bills of materials required by each takt wagon were also added. By doing this an appropriate material package was linked to every work package of the takt plan. The material management process was presented, and the corresponding software was demonstrated by the logistics contractor to the first author.

As per a process map created by the logistics operator, the materials were delivered depending on their type through one of two types of flow: (1) The large and heavy materials such as gypsum boards and bricks were delivered using an off-site warehouse as a buffer to level the flow. The material management system produced a plan for daily picking and delivery from the off-site warehouse to the site and eventually to the corresponding takt area on a just-in-time basis one takt time ahead of the work package. (2) For smaller materials such as water faucets and light switches, an on-site area was provided for the trade partners to be used as a supermarket-like buffer. These materials were delivered directly to the site supermarket and picked by the trade partners as required by the takt schedule. The supermarket area was also used as a one-day buffer against expected delivery failures. (Q1)

Through site observations and interviews it was verified that the material buffers on site were able to be kept small which helped avoid congestions and unnecessary moving. The average material buffer was estimated to have been on average no more than one day's worth for most of the logistically important material types. The site management also felt that the daily delivery plans simplified the daily management of the logistics even if they were not meticulously followed and controlled. (Q2)

Even with such lean material buffers a lack of materials due to supply disruptions was reported as not having been a major problem for the flow of work, which leads to the conclusion that the material management process was reliable enough to enable them. (Q3)

Continuous improvement: The interviews indicated that occasionally during the project, out-of-standard conditions compared to the planned work processes were spotted and meetings to manage the specific issues were held (Q1) and due to the held meetings, several sources of waste were reduced during the project. (Q2) This is in alignment with the general expectation that explicitly defined work processes enable continuous improvement efforts to tackle issues in a formal way. (Q3)

Visual management: As observed during the site visits, the takt plans were printed out on large sheets of paper and put on display in the daily huddle area. Smaller versions of the same sheets were posted on site in common walking areas such as staircases. 4D animations of the takt process and operations flow were created and kept running on displays in the daily huddle area. The hotel room numbers were painted on the floor in the corridors in front of the room entrances. (Q1)

According to the PMO, the workers were frequently found around the posted takt plans either discussing their issues with each other or reminding themselves of which area they were supposed to work in and go to next. Taking note of the room numbers in the takt plan, the painted room numbers made it easy for them to be sure about the correct work location. The 4D animation of the operations flow made the takt train highly visible which presumably helped in gaining common understanding about the direction of the flow. The process flow 4D animation was suspected to be mostly helpful in gaining initial understanding about the sequence of work for newcomers to the project (Q2)

The painted room numbers were unanimously considered as very helpful for orientation at the site and as they were easy to create, the idea was found to be a true low hanging fruit. The

4D animations seemed helpful at the start but updating them to take into account every takt control adjustment was considered too burdensome to do. (Q3)

Integration of design: (Q1) There was a defined documented process for escalating design problems surfaced during production according to the size of the problem and the level of involvement required. A presentation witnessed also by the first author was given to the designers to inform them about the takt process and the urgency of solving problems as they appear. In addition, an interview revealed that in order to make the urgency feel more real, the designers were invited to visit the site shortly after the beginning of the takt phase intentionally to let them see for themselves the hectic nature of the production flow. After this a response time of one takt was sought in order to tackle the problems that can be solved quickly.

The interviews with the management team of the takt phase confirmed that the designers were better prepared to being on call during the takt phase due to at least in part the involvement initiative. Involving the designers personally with the takt phase helped to create clear lines of communication between the site and the designers, and the sense of urgency to solve problems reached the design team. (Q2)

According to the site management, the explicitly defined escalation process was not strictly enforced. This was mostly because solving most issues was too straightforward to warrant any need for a formal process. (Q3)

First-run study: According to interviews and witnessed during a site visit, a mock-up of one typical hotel room was planned and built off-site in order to gain knowledge about the potential problems in the details of the work steps. (Q1) However, because the mock-up was not completely finished before the start of the takt phase its usefulness was limited to the planning phase. (Q2) In order to gain benefits from a first-run study, the process needs to be planned and managed adequately in advance of production. (Q3)

Digitalization: The logistics contractor managed the material flows with a digital materials management system, which was presented to the first author by the logistics contractor. The material management software was also developed for the purposes of the project by the software vendor. Quality control was also managed with a digital cloud platform, to which the first two authors had access. (Q1)

The digital material management system allowed the logistics operator to print out sheets of daily material deliveries for management of picking the materials at the off-site warehouse, packing them into delivery trucks and transporting them to takt areas on site. According to the logistics operator the system reduced manual work in handling the logistics information flows, simplified management and enforced good adherence of the materials flow to the takt plan. The digital quality management system is also generally considered to reduce manual work. (Q2)

The digital footprints of the systems reinforce the view that the materials management system was coupled with a planned workflow that the users were trained in while the quality management system lacked tight coupling with the takt. From this it can be presumed that in order to take full advantage of digital tools, management processes should also be defined and adhered to. (Q3)

DISCUSSION

The decision to use takt production in the project was made early by the project management who had learned about its potential as a lean construction concept. Takt quickly became a dominant theme and emerged as the foundation to link together the treated lean construction concepts in Figure 1. In the planning and preparation phase, takt drove the need for the enabling requirements of top management support and planning effort. The supporting conditions of collaboration, continuous improvement, integration of design and integrated logistics revolved around the takt plan. The takt production concepts of a 4-hour takt-time, daily management and takt control adjustment mechanisms during production were new to most of the management team but worked as an essential part of their operating system. The tools visual management, first-run study and digitalization were all taken in to serve the functioning of the takt phase. All in all, it seems clear that the decision to use takt production was the key to make the parts come together.

More than that, it was evident that the relationship of the individual concepts with the takt and each other leveraged their benefits. For example, visual management techniques and digital tools facilitated collaboration between trade partners, the logistics operator, designers and the site management team, which happened at the level of daily management, which in turn was enabled by thorough planning at the level of a very small batch-size. The short takt time required a lot of attention to details both in planning and operating, which also worked to bring the stakeholders very close together.

It is therefore suggested that this study of the case project validates the hypothesis that takt production can work as a ground up driver towards implementing a system of interrelated lean production ideas in construction. This does not provide nor negate the desire to search for a new theory-based methodology for construction that draws inspiration from lean production as outlined in the introduction but aims to help in bridging the gap.

As an interesting result from the study, it is wondered whether the enabling requirement of top management support could be argued as the even more important concept than takt production for the success of the project. On the one hand, in the absence of the pressure from the site's top manager, the application of takt production and in consequence all the other concepts would most probably have been less stringent and the benefits highly diluted. On the other hand, takt production was the instrument that enabled applying the pressure.

As limitations of this study, it must be noted that the nature of the data was unstructured and did not fit well for a systematic approach. That being the case, the discussion and conclusions in the findings section represent mostly inferences of the authors through heuristics and experience instead of a rigorous analysis. The study relied heavily as a data source on interviews that are anecdotal and therefore of only limited qualitative value. The findings represent only one case project and are therefore not generalizable.

CONCLUSIONS

Returning to the research question of whether takt production can function as a driver for change from an application of lean production methods in a scattered way to a system where the concepts work together, the case project does indeed suggest that the hypothesis may be valid. As described in the discussion section, all the identified lean production methods related in an important way to the takt and would have lost a lot of their benefits in the absence of the takt. Particularly the short takt time created the sense of urgency needed to force the concepts to come together.

However, even if takt was the engine that made the system run, it needed as its fuel the exceptional involvement of the site management team and a constant input from the leadership in the form of coaching and encouragement. It seemed clear that the takt phase would have gone very differently in the absence of these, which lets us conclude that we should not see takt production as a wonder weapon but rather as a solid foundation for a system.

Future research could further validate this suggestion by designing and running an experiment of improvement effort where takt production is explicitly put at the core and other lean construction concepts are built around it as supporting functions.

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ANALYZING THE LEAN PRINCIPLES IN INTEGRATED PLANNING AND SCHEDULING METHODS

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ABSTRACT

The shortcomings and limitations of conventional planning and scheduling methods led to a great deal of emphasis on combining them and developing integrated scheduling methods. Also, lean principles and tools are included in the integrated scheduling methods' structure to develop more effective scheduling strategies. This paper implements a multi-step methodology to identify and analyze the lean principles utilized in integrated scheduling methods. The findings show that integrated scheduling methods, Building Information Modelling (BIM)-Last Planner System (LPS)-Kanban, BIM-LPS, Location-based Management System (LBMS)-LPS-CPM, and BIM-LBMS have included a variety of lean principles into their frameworks. Moreover, improving the reliability of the planning, increasing transparency, identifying and eliminating waste, detecting and solving spatiotemporal conflict, enabling the coordination of the look-ahead plans, and continuous flow of work have received the most attention in the integrated scheduling methods. This paper contributes significantly to the body of knowledge by raising project stakeholders' awareness of the lean principles utilized in integrated scheduling methods in construction projects.

KEYWORDS

Lean principles, Integrated Scheduling Methods, SNA, Quantitative Analysis

INTRODUCTION

The construction industry remains still among the lowest productivity rates across all sectors (Turner et al. 2020). Ineffective planning and scheduling (Al Hattab and Hamzeh 2016; Salama et al. 2021), a lack of effective communication and collaboration between stakeholders (Hamzeh et al. 2019; Khanzadi et al. 2020), unrealistic scheduling and inefficient resource management (Hamza et al. 2022) are some reasons for this issue. Thus, it consistently seeks innovative and productive methods for optimizing projects, reducing waste, and increasing efficiency. To overcome the challenges related to ineffective planning and scheduling, using lean principles and tools combined with conventional scheduling methods and developing

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integrated scheduling methods is an approach that has received considerable attention in recent years. (Abbasi et al. 2020; Aslam et al. 2020; Boton et al. 2021; Heigermoser et al. 2019). In line with this, several studies integrated the Last Planner System (LPS) with Building Information Modelling (BIM) to improve productivity and efficiency, promote continuous improvement, increase understanding of project stakeholders, and improve the reliability of the planning (Barkokebas et al. 2021; Heigermoser et al. 2019; Sacks et al. 2010; Schimanski et al. 2020; Schimanski et al. 2021). In addition, Abdelmegid et al. (2021) established a framework for adopting simulation modelling in construction by integrating the LPS with simulation modelling approaches. Novinsky et al. (2018) combined the LPS with Earned Value Management (EVM) to improve transparency and control project progress concerning time and cost. Moreover, Ammar (2013) integrated the Critical Path Method (CPM) and Line of Balance (LOB) to consider both logic dependency and resource continuity constraints for repetitive projects. Seppänen et al. (2010) developed an approach that combined the benefits of LPS and Location-based Management System (LBMS) to achieve the lean goals of decreasing waste, increasing productivity, and decreasing variability. Although integrated scheduling methods have primarily addressed the shortcomings of traditional and common scheduling methods, like CPM, and provide the project manager with a wider range of capabilities, a lack of understanding of their underlying concept and incredibly lean principles used make it challenging for the project manager and scheduler to choose the practical and required approach for planning and scheduling.

This study seeks to identify and assess a list of lean principles utilized in integrated scheduling methods in the construction industry. Furthermore, it provides project managers, planners, and schedulers with new insights into the underlying lean principles used in integrated scheduling methods to improve planning and scheduling effectiveness. The following sections provide an overview of the research methodology, analyses and results, a discussion of research findings, and, eventually, recommendations for further research in this field of study.

RESEARCH METHODOLOGY

As shown in Figure 1, a multi-step methodology is employed to achieve this study's objectives.

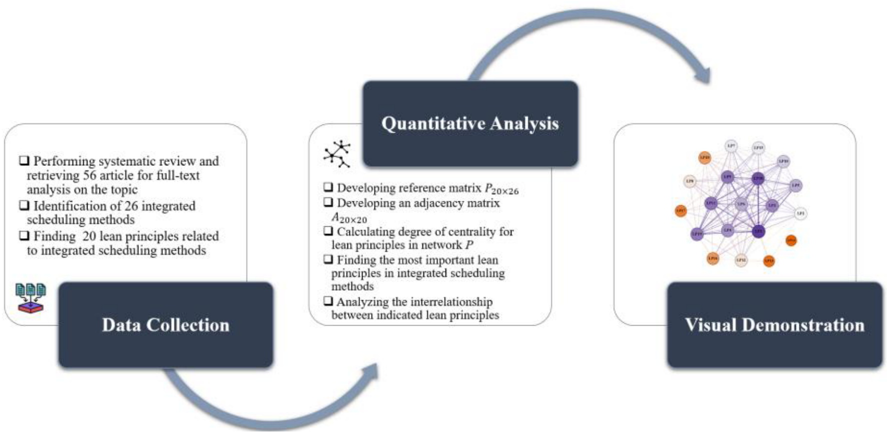

Figure 1: A brief overview of the adopted multi-step research methodology

This study's methodology consists of the following steps: (1) a Systematic Literature Review (SLR) on integrated planning and scheduling methods in the construction industry; (2) identification of lean principles applied in the integrated scheduling methods; and (3) using Social Network Analysis (SNA) to quantify most important lean principles in the integrated scheduling methods. The following sections outline the research methodology's components in more detail.

SYSTEMATIC LITERATURE REVIEW

The applied SLR consists of three components: (1) paper identification, (2) screening; and (3) content analysis conducted by a quantitative literature analysis using SNA. Conference proceedings and peer-reviewed construction journal papers were considered to collect data. As shown in Table 1, the search string was created by combining scheduling methods with "AND" and "OR" in the Web of Science (WoS) database. Title, abstract, and keywords were searched till December 2022, resulting in 1283 publications.

Table 1: Search keywords

Search Query
TS=(("CPM" OR "Critical Path Method" OR "PERT" OR "CCPM" OR "Critical Chain Management system" OR "Critical chain method" OR "LOB" OR "Line of Balance" OR "LPS" OR "Last Planner System" OR "Takt Planning" OR "Takt time planning" OR "LBMS" OR "Location Based Management System" OR "BIM" OR "Building Information Modeling" OR "4D" OR "4DBIM" OR "Linear Scheduling Method" OR "LSM" OR "Simulation" OR " Monte-Carlo") AND ("Project Planning" OR "Project Scheduling" OR "Construction Planning" OR "Construction Scheduling"))

The screening phase is conducted based on several inclusion criteria, such as choosing articles written in English and including at least one combination of scheduling methods (i.e. LPS-LSM). After the screening phase, content analysis was performed on 56 acquired papers to identify the lean principles used in the integrated scheduling methods. To do this, the finalized papers based on 26 identified integrated scheduling methods were analyzed and coded using Nvivo Qualitative Data Analysis software to extract the lean principles associated with each integrated scheduling methods. After that, first, 26 integrated scheduling methods were considered essential and beneficial for the aim of this study. Second, 38 lean principles were extracted from 56 approved papers. The authors tried to aggregate the principles with same concept such as reducing the cycle time with identifying and eliminating of wastes, resulting 20 lean principles for further analysis. It should be mentioned that the codifying and extracting lean principles were applied by this research's first author and evaluated and approved by the other authors of the article.

QUANTITATIVE ANALYSIS OF LEAN PRINCIPLES

The SNA facilitates researchers' efforts to discover systematic literature-related outcomes by connecting concepts, themes, and ideas missed by manual review evaluations due to its quantitative strength and capacity to evaluate interrelationships among numerous factors (Elsayegh and El-adaway 2021). So, same as other studies for quantitative analysis of the collected data from the literature (Assaad and El-Adaway 2020; Elsayegh and El-adaway 2021; Hosseini et al. 2018; Saedi et al. 2022), the authors chose SNA as the best approach for assessing and identifying the most highlighted lean principles in the integrated scheduling methods. A reference matrix P must first be developed to perform SNA on the extracted lean principles. The rows of this matrix reflect recognized lean principles, while the columns indicate integrated scheduling methods. The second step is constructing an adjacency matrix based on the reference matrix P. A weighted adjacency matrix is computed by multiplying the reference matrix P by its transpose and then removing and replacing the values in the diagonal cells of the resulting matrix with zeros. Equation 1 is used to construct this matrix. This matrix represents a network where the rows and columns represent lean principles, and the cell values indicate the co-occurrence frequency of each lean principle.

$$A_{l\times l} = \begin{cases} P_{l\times m} \times P_{l\times m}^{T} & for\ i \neq j \\ 0 & for\ i = j \end{cases} \tag{1}$$

Where $A_{l \times l}$ = weighted adjacency matrix; $P_{l \times m}$= reference matrix; $P_{l \times m}^{T}$= transpose of the reference matrix where i and j are the row and column indexes of the reference matrix, respectively.; l = the number of identified lean principles (i.e., 20); and m = the number of integrated scheduling methods (i.e., 26).

In addition, degree centrality (DC) was utilized to evaluate the significance of a given lean principle based on its frequency and association with other lean principles. The DC for each lean principle is calculated based on Equation 2.

$$DC_i = \sum_{j;j \neq i} P_{i,j} \tag{2}$$

Where DC_i is the degree of centrality for lean principle i and $P_{i,j}$ is the value of the cell in row i and column j of the adjacency matrix. Since the DC calculation depends on the size of the relevant network, it was decided to normalize it. According to Equation 3, the normalized DC of a lean principle i in a network equals the DC of the evaluated lean principle divided by the highest DC of the network.

$$\overline{DC_i} = \frac{DC_i}{max\,\{DC_k\}} \tag{3}$$

Therefore, all lean principles reflect a DC_i normalized between 0 and 1.

RESULTS AND ANALYSIS

The systematic search and screening efforts provided 56 approved journal and conference papers from 1994 to 2021, as indicated in the methodology. By reviewing the contents of the papers, the authors found 20 lean principles in 26 integrated scheduling methods, detailed in Table 2 and Table 3. As shown in Table 3, the 26 integrated scheduling methods were established by merging 14 conventional scheduling methods with lean tools, such as the last planner system, Kanban, six sigma, Just-in-Time (JIT), and takt time. Furthermore, Figure 2 shows the mapping of studied integrated scheduling methods and the identified lean principles. Purple cells indicate that the integrated scheduling methods have attempted to meet lean principles. BIM-LPS-Kanban, BIM-LPS, LBMS-LPS-CPM, and BIM-LBMS have incorporated various lean principles into their frameworks.

Table 2: Identified lean principles

ID	Lean Principles
LP1	Improving the reliability of the planning
LP2	Increasing productivity
LP3	Continuous flow of work
LP4	Decreasing workflow variability
LP5	More efficient constraints analysis
LP6	Visualizing of schedules to understand and communicate content to a variety of stakeholders
LP7	Avoiding omissions and sequencing mistakes
LP8	Schedule constructability analysis
LP9	Identifying and eliminating of waste
LP10	Decreasing meeting durations
LP11	Detecting and solving spatiotemporal conflicts
LP12	Maintaining continuity of resources
LP13	Scheduling of modular and offsite construction
LP14	Eliminating the root causes of variability
LP15	Reducing of production cycle time
LP16	Improving the usability of the 4D BIM for workflow analysis
LP17	Increasing safety on construction sites
LP18	Increasing transparency
LP19	Enabling the coordination of the lookahead plans
LP20	Implementing of pull flow control

Table 3: Highlighted integrated scheduling methods

ID	Integrated Scheduling Methods	Abbreviations
1	4D BIM-Last Planner System	4D-LPS
2	4D BIM-Linear Scheduling Method	4D-LSM
3	BIM-Just In Time	BIM-JIT
4	BIM-Location-Based Management System	BIM-LBMS
5	BIM-Last Planner System	BIM-LPS
6	BIM-Last Planner System-Kanban	BIM-LPS-Kanban
7	BIM-Simulation Modeling	BIM-SM
8	BIM-Takt Time Planning	BIM-TTP
9	BIM-Takt Time Planning- Simulation Modeling	BIM-TTP-SM
10	Critical Chain Project Management- Last Planner System	CCPM-LPS
11	Critical Chain Project Management- Last Planner System- Linear Scheduling Method	CCPM-LPS-LSM
12	Critical Path Method- Location-Based Management System	CPM-LBMS
13	Critical Path Method- Last Planner System	CPM-LPS
14	Earn Value Management- Last Planner System	EVM-LPS
15	Location-Based Management System- Critical Chain Project Management	LBMS-CCPM
16	Location-Based Management System- Last Planner System- Critical Path Method	LBMS-LPS-CPM
17	Line of Balance - Critical Path Method	LOB-CPM
18	Line of Balance- Monte Carlo Simulation	LOB-Monte Carlo
19	Last Planner System-BIM-Simulation Modeling	LPS-BIM-SM
20	Last Planner System- Location-Based Management System	LPS-LBMS
21	Last Planner System- Line of Balance- Simulation Modeling	LPS-LOB-SM
22	Last Planner System- Six Sigma	LPS-SS
23	Linear Scheduling Method- Critical Chain Project Management	LSM-CCPM
24	Last Planner System- Simulation Modeling	LPS-SM
25	Critical Path Method- Simulation Modeling	CPM-SM
26	Linear Scheduling Method- Critical Chain Project Management- BIM	LSM-CCPM-BIM

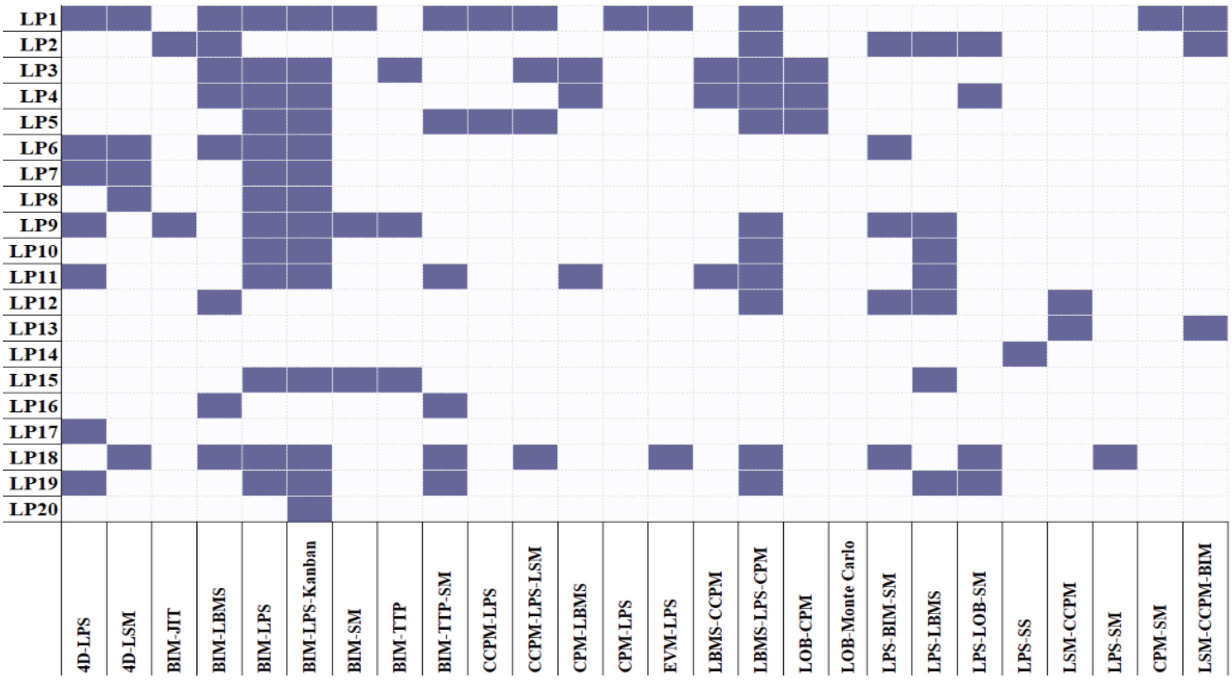

Figure 2: Mapping of studied integrated scheduling methods and the identified lean principles

QUANTITATIVE ANALYSIS OF LEAN PRINCIPLES

After conducting an in-depth analysis of the papers and identifying the lean principles, a reference matrix P was created based on those lean principles and integrated scheduling methods. The reference matrix P has a size of 20 by 26 and comprises 20 lean principles and 26 integrated scheduling methods. The following subsections describe the results.

Lean Principles Network

Using Equation 1, the authors created the adjacency matrix based on the reference matrix acquired from the literature analysis. The adjacency matrix's cell values indicate the weight of the edge connecting one node to another. The cells are color-coded based on the intensity of the edges between the pair of lean principles, illustrated in Figure 3. As can be seen, white-colored cells for a pair of lean principles imply that they have not co-occurred in any of the evaluated integrated scheduling methods. Consider LP2 (increasing productivity) and LP8 (schedule constructability analysis) for the latter. On the other hand, certain pairs of lean principles have dark orange cells, suggesting significant weights and, therefore, an abundance of co-occurrence in the integrated scheduling methods under consideration. This is represented in the edge weights between LP1 (improving the reliability of the planning) and LP18 (increasing transparency).

Moreover, as illustrated in Figure 4, the adjacency matrix is employed to visualize the lean principles network. The network diagram consists of 20 lean principles (nodes) linked by 266 directed edges or connections. The figure demonstrates that the network has several links between lean principles. In other words, the network of lean principles is dense, indicating numerous interconnections resulting from graph density equal to 0.778.

The degree of centrality (DC) is calculated and normalized to assess the interconnectivity among the lean principles in integrated scheduling methods. Table 4 displays the normalized DC results. In Figure 4, the dark purple colors correspond to lean principles with higher DC values, and the orange colors represent lean principles with lower DC values.

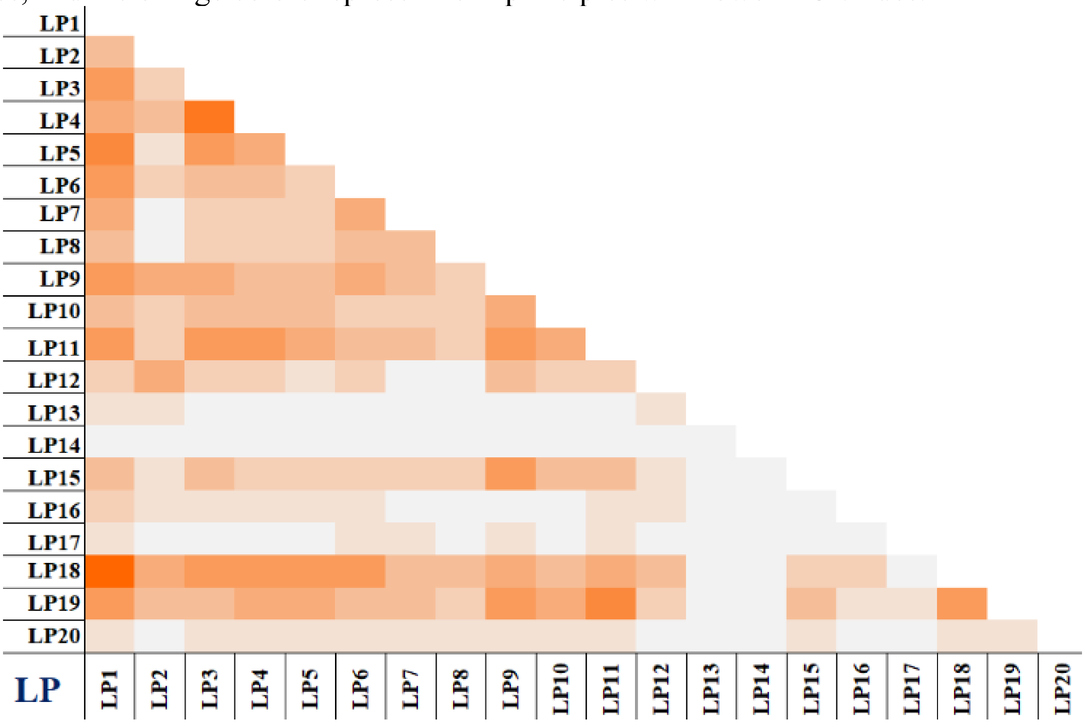

Figure 3: Color-coded adjacency matrix of lean principles

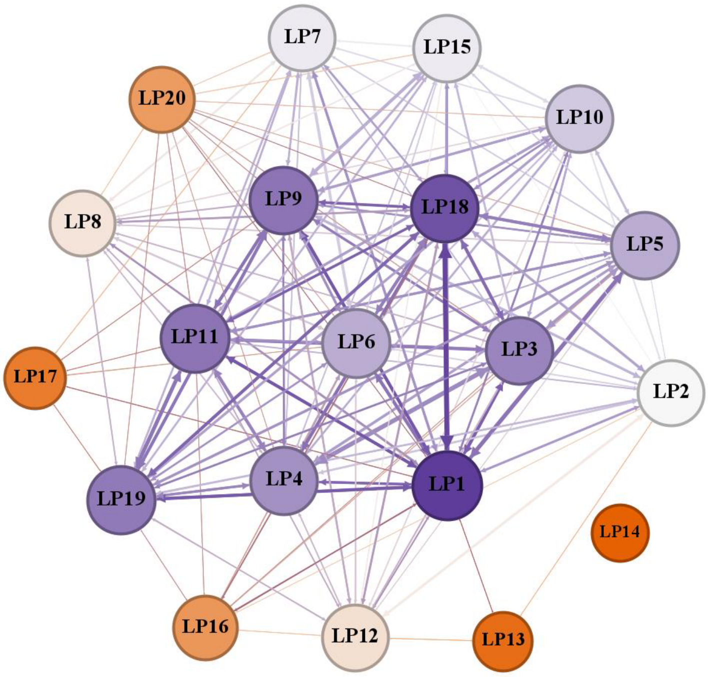

Figure 4: Lean principles network

Table 4: Normalized DC for lean principles

Code	Lean Construction Principles	Network P Normalized DC
LP1	Improving the reliability of the planning	1.00
LP18	Increasing transparency	0.94
LP9	Identification and elimination of waste	0.85
LP11	Detecting and solving spatiotemporal conflicts	0.85
LP19	Enabling the coordination of the look-ahead plans	0.83
LP3	Continuous flow of work	0.80
LP4	Decreasing workflow variability	0.77
LP5	More efficient constraints analysis	0.70
LP6	Visualization of schedules to understand and communicate content to a variety of stakeholders	0.70
LP10	Decreasing meeting durations	0.62
LP7	Avoiding omissions and sequencing mistakes	0.53
LP15	Reduction of production cycle time	0.53
LP2	Increasing productivity	0.50
LP8	Schedule constructability analysis	0.44
LP12	Maintaining continuity of resources	0.42
LP20	Implementation of pull flow control	0.20
LP16	Improving the usability of the 4D BIM for workflow analysis	0.18
LP17	Increasing safety on construction sites	0.09
LP13	Scheduling of modular and off-site construction	0.05
LP14	Eliminating the root causes of variability	0.00

Two perspectives on lean principles can be discussed: (1) the lean principles that have been employed most often in integrated scheduling methods, and (2) the lean principles that have been used the least frequently.

In regards to the first viewpoint, as shown in Figure 4 and Table 4, LP1 (improving the reliability of the planning), LP18 (increasing transparency), LP9 (identification and elimination of waste), LP11 (detecting and solving spatiotemporal conflicts), LP19 (enabling the coordination of the look-ahead plans), LP3 (continuous flow of work) have received the most attention in the integrated scheduling methods.

Following the second perspective, Figure 4 indicates that LP13 (scheduling of modular and off-site construction), LP17 (increasing safety on construction site), LP16 (improving the usability of the 4D BIM for workflow analysis), and LP20 (implementing of pull flow control) have been given the least importance by the integrated scheduling methods. Moreover, as seen in the network, there is no link for LP14 (eliminating the root causes of variability), indicating a lack of consideration for this principle in the integrated scheduling methods.

RESEARCH DISCUSSIONS

This section discusses the important results of this research in the context of identified lean principles in the integrated scheduling methods. This can be accomplished by highlighting areas that have gained considerable attention and those that have received little attention to determine future directions.

Understanding these integrated methods and the underlying concepts can enable project managers to optimize resources and processes more effectively. In support of this claim, several studies have discussed that a lack of knowledge and understanding of project scheduling methods, tools, and underlying concepts may lead to failures in project delivery (AlNasseri and Aulin 2015; Shash and Ahcom 2006). In this respect, this research investigated identifying and analysing the lean principles employed in integrated scheduling methods to assist project stakeholders in understanding the effectiveness of integrated scheduling methods. The findings indicated that the Last Planner System (LPS), Kanban, six sigma, Just-in-Time (JIT), and takt time were the most utilized lean tools in the integrated scheduling methods. Although many integrated scheduling methods, such as BIM-LPS, BIM-LPS-Kanban, LBMS-LPS, LPS-CPM, LPS-LSM, etc., have benefited from LPS advantages such as planning reliability, constraint management, continuous workflow, and continuous improvement, few integrated scheduling methods have focused on one of its shortcomings, which is the non-performance of root cause analysis and corrective actions (Aslam et al. 2020). In addition, the focus of some integrated scheduling methods, such as LPS-4D, LPS-BIM, and LPS-BIM-Kanban, on addressing one of LPS drawbacks, which is inadequate visualization capabilities (Aslam et al. 2020), demonstrates that there is a great deal of potential for the future of the industry, as well as research to focus on visual-based collaborative scheduling methods including Virtual Reality (VR)-LPS and metaverse-base LPS.

The results of the lean principles network illustrated that in the integrated scheduling methods, LP1 (improving planning reliability), LP18 (increasing transparency), LP9 (identifying and eliminating of waste), LP11 (detecting and solving spatiotemporal conflicts), LP19 (enabling coordination of the look-ahead plans), and LP3 (continuous flow of work) have were given the most attention. These results indicate that in line with efforts to increase productivity in the construction industry, the focus of research and industry for project planning and scheduling is beyond cost, time and quality management, which has been of concern for years. Areas such as reliability, transparency, waste management, coordination in mid-term planning, and flow and process management are considered more attention in integrated scheduling systems. Moreover, attention to workspace management through location-based scheduling methods, such as LOB, LBMS, and LSM, as well as object-based scheduling methods, including 4D and BIM in integrated scheduling methods, lead to focus has been directed at LP11 (detecting and solving spatiotemporal conflicts).

In the other hand, LP14 (eliminating the root causes of variability), LP13 (scheduling of modular and off-site construction), LP17 (increasing safety on the construction site), LP16 (improving the usability of the 4D BIM for workflow analysis), and LP20 (implementing of pull flow control) have received the least consideration in integrated scheduling methods. The findings show that although learning and eliminating the root causes of variability is one of the important principles in lean construction and extensively studied in the early days of lean construction, it has received little attention in integrated scheduling methods, this issue can also be found in Aslam et al. (2020)'s research. One possible explanation is that lean construction is a subset of the broader idea of lean thinking, which embraces various principles and activities to enhance productivity and quality while minimizing waste. Variability may be managed holistically and completely by combining lean construction with other principles, including, collaboration and communication management, continuous improvement and visual management. By focusing on these proactive actions, the need to address variability as a separate issue may be reduced or managed indirectly. In addition, little emphasis has been given to the scheduling of modular and off-site construction in integrated scheduling methods, despite the fact that one way to incorporate lean production into construction project delivery would be to enhance off-site construction levels from materials, components and sub-assembly to modular buildings (Pasquire and Connolly 2002). Furthermore, 4D BIM capabilities have contributed significantly to the use of lean principles, such as LP6 (visualizing of schedules to understand and communicate content to a variety of stakeholders) and LP11 (detecting and solving spatiotemporal conflicts), and LP8 (schedule constructability analysis), in integrated scheduling methods. However, little attention is paid to the usability of the 4D BIM for workflow analysis. This gap can be investigated in future research on integrated scheduling methods.

Analyzing the co-occurrence of used lean principles in integrated scheduling methods, based on Figure3, depicts the pairs of LP1 (improving the reliability of the planning) and LP18 (increasing transparency), LP4 (decreasing workflow variability) and LP3 (continuous flow of work), and LP19 (enabling the coordination of the look-ahead plans) and LP11 (detecting and solving spatiotemporal conflicts) have been recognized as the most frequent pairs in integrated scheduling methods. According to these evaluations, considering lean principles in integrated scheduling methods focuses mainly on mid (look-ahead) and short-term (weekly work) planning.

In integrated scheduling methods such as BIM-LPS, and BIM-LPS-Kanban, which combine LPS and BIM capabilities, lean principles have been covered to a considerable extent; however, in order to apply these concepts practically, one must utilize more integrated methods to overcome the challenges of mismatched LoD in BIM and the granularity of look-ahead (Lin and Golparvar-Fard 2021) and weekly work plans, covering all scheduling levels, and taking contract and management requirements into account. For this purpose, the authors propose using location-based scheduling methods, such as LBMS and Takt Time Planning (TTP), for work structuring and solving the mismatching LoD in BIM with look-ahead and weekly work plans granularity by associating BIM components to their locations. Moreover, since CPM-based scheduling is a contractual obligation for many projects, including it in integrated scheduling methods will also address managerial and contractual concerns.

CONCLUSION

As a result of poor productivity resulting from ineffective project planning and scheduling in the construction industry, not only have numerous studies examined the integration of conventional scheduling methods with each other, lean tools and principles, but also, in practice, project managers and planners put a greater emphasis on using integrated scheduling methods for more effective project scheduling and control. To better understand the lean principles used in integrated scheduling methods, this study followed a multi-step methodology to analyze 26 identified integrated scheduling methods and 20 lean principles. To this end, a systematic literature review is conducted on the planning and scheduling field of study. After that, a quantitative analysis was performed based on SNA. The degree of centrality (DC) is determined to assess the importance of lean principles used in integrated scheduling methods. The result indicated that BIM-LPS-Kanban, BIM-LPS, LBMS-LPS-CPM, and BIM-LBMS, as some integrated scheduling methods, have utilized the most lean principles in their structures that indicate the most focus of academia and industry is on the LPS and BIM for developing the integrated scheduling methods.

As lean principles, LP1 (improving the reliability of the planning), LP18 (increasing transparency), LP9 (identification and elimination of waste), LP11 (detecting and solving spatiotemporal conflicts), LP19 (enabling the coordination of the look-ahead plans), and LP3 (continuous flow of work) have gained the most attention in the integrated scheduling methods. In addition, the pair of LP1 (improving the reliability of the planning) and LP18 (increasing transparency) were detected as the most pairs in integrated scheduling methods. The findings illustrate that the construction industry's push for improving productivity has led to a shift in research and industry focus away from traditional concerns of cost, time, and quality management in project planning and scheduling.

In contrast, LP14 (eliminating the root causes of variability), LP13 (scheduling of modular and off-site construction), LP17 (increasing safety on construction site), LP16 (improving the usability of the 4D BIM for workflow analysis), and LP20 (implementation of pull flow control) have paid the least attention in integrated scheduling methods. Despite the potential benefits of incorporating lean production principles into construction project delivery through increased levels of off-site construction, integrated scheduling methods have overlooked the scheduling of modular and off-site construction. This represents a gap in the current focus, as enhancing the use of off-site construction - from materials, components, and sub-assemblies to modular buildings - could be a viable strategy for achieving this goal.

Finally, this paper contributes to the body of knowledge by enhancing knowledge and awareness of the lean principles used in integrated scheduling methods in the construction industry.

The limitations of this research are the lack of analyzing correlation between lean principles and considering the expert's points of view for evaluating lean principles. Moreover, focusing on collaborative visual-based scheduling using new technologies such as Virtual Reality (VR)-LPS and metaverse-base LPS could be one of the suggestions for further research. Future studies should also focus on several lean principles, such as root cause analysis and corrective actions, the usability of 4D BIM for workflow analysis, and modular and offsite construction scheduling for integrated scheduling methods.

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A NARRATIVE REVIEW OF WORKSPACE PLANNING IN CONSTRUCTION: CHALLENGES AND INSIGHTS

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ABSTRACT

Space on construction sites is not abundant as may be thought. In fact, workspace planning could become increasingly challenging at times. Moreover, improper workspace planning may lead to congestion and, hence, potential safety and productivity issues. Workspace planning aligns with Lean thinking through reducing wastes in workers' productivity, waiting time, double handling, and different types of flow. Meanwhile, there is generally a scarcity of research studies in this area especially in industrial projects. As such, this paper presents a narrative literature review of research conducted on workspace planning in construction. Specifically, the review aims to answer the following questions: What is a workspace? What are some methods used for workspace planning? What are the challenges faced in workspace planning? What decisions are essential for workspace planning? The last question tackles fundamental concepts in workspace planning such as flow types, area patterns, workspace classification structure, and spatial-temporal conflict identification and resolution. The study concludes with considerations to be scrutinized and adopted during the process of developing a well-thought-off workspace planning system.

KEYWORDS

Workspace, planning, spatial-temporal conflict, flow, area.

INTRODUCTION

Generally, evaluating space requirements and positioning construction operations to predetermined locations on site are often left until the project starts. It may be believed that space is abundant in a way that eliminates the need for prior planning; however, this is a fallacy. Proper workspace planning is necessary to avoid needless material handling, prevent spatial-temporal conflicts, and reduce travel times (Tommelein & Zouein, 1993). A workspace is a shared resource among all participants on a project, and every person on a construction project needs a separate workspace to carry out their tasks. Accordingly, improper workspace planning might lead to interferences between different crews, creating congestion that results in safety and productivity issues (Hammad & Zhang, 2011; Mallasi, 2006). Workspace management aims to ensure that workspace demand and availability match, thereby avoiding spatial conflict (Igwe et al., 2020).

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However, the available scheduling methods have proved to be less sufficient for workspace planning because they neglect the spatial feature of each task. For instance, the Line-of-Balance (LOB) method considers that only a single crew can occupy each work zone at once, and it treats the space as a scalar one-dimensional variable, which omits substantial complexity faced when managing 3D space (Choi et al., 2014). This complexity could explain why researchers have replaced 2D sketches and 2D computer-aided design models used for workspace analysis (e.g., Zouein & Tommelein, 2001, Guo, 2002) with 4D and 5D BIM models that better represent the actual complexity of the real workspace (e.g., Chavada et al., 2012; Moon et al., 2014; Rohani et al., 2018). However, most of the existing 4D (3D + time) simulations are static where objects are generated in the simulation at discrete points in time, such as at task start point. Still, in reality, construction is dynamic, and the products appear progressively as they are built (Heesom et al., 2003). Moreover, a construction activity might require more than one workspace of varying geometry throughout different stages (Su & Cai, 2014). Thus, the construction workspace constantly changes, but such change is poorly assessed in current literature, especially for industrial projects (Bannier et al., 2016). For a workspace modelling approach to be effective, it needs to convey the actual workspace usage accurately and flexibly. Although a variety of 4D simulation models allowing full navigation through the model across time is available in the market, none of them adequately supports the scheduler during schedule preparation. These models primarily focus on visualizing the already completed schedules (Tulke et al., 2008). Additionally, spatial-temporal conflicts can be prevented through employing rules to control the movement of workers, equipment, and material. However, developing the rules that govern how the cells behave is difficult, particularly when there are many rules (Hammad & Zhang, 2011).

In short, workspace planning is complex in nature and entails a variety of decisions that are contingent on the distinct requirements of each workspace. Specifically, evaluating the initial requirements of and the continuous spatial-temporal change in the location and dimension of each workspace (i.e., through time and across all three dimensions) could be a major challenge in workspace planning. Meanwhile, there is generally a scarcity of academic research, especially in industrial projects (Bannier et al., 2016), that provides detailed analyses of workspace requirements, dynamic behaviours of workspaces, and impacts of different tasks on a workspace. As such, this paper presents a narrative literature review of research conducted on workspace planning in construction. A narrative literature review intends to "assemble and synthesize extant literature and provide readers with a comprehensive report on the current state of knowledge in the area under investigation" (Templier & Paré, 2015). In this context, this study first presents the definition of workspaces in construction, a brief review of some existing workspace planning methods, a description of some of the challenges encountered in workspace planning, and then highlights a set of considerations that must be accounted for in construction workspace planning.

METHODOLOGY

This study followed a review procedure similar to the six-step procedure proposed by Templier & Paré (2015) for conducting literature reviews, which includes (1) formulating the problem, (2) searching the literature, (3) screening for inclusion, (4) assessing quality, (5) extracting data, and (6) analysing and synthesizing data. It should be noted that the quality assessment of the studies was limited to their relevance to the defined problem, their clarity, and their contribution to the body of literature found on the topic. As such, the research design and methods used in the studies were not evaluated. Moreover, given the limited size of research conducted on workspace planning in construction, the initially formulated problem in Step 1 was aimed to identify studies generally conducted on workspace planning in construction. The next step consisted of conducting an initial search for relevant studies published in reputable journals (e.g., *Automation in Construction*, *Journal of Construction Engineering and Management,* etc.) in order to determine significant research areas on the topic. Upon completing this initial search and screening the full texts of the identified studies, Step 1 was revisited to formulate more specific research questions in order to better direct the search process. As such, the following questions were formulated: *What is a workspace? What are some methods used for workspace planning? What are the challenges faced in workspace planning? What decisions or considerations are essential for workspace planning?* Next, for each question, the literature was searched for relevant studies (Step 2), and the studies were screened for data pertinent to the question of interest (Steps 3, 4, and 5). Finally, the data extracted for each question was synthesized to provide a summary that helps the reader understand the current state of knowledge on the topic (Step 6).

DEFINITION OF WORKSPACE

Construction crews need space to execute work and to move, fabricate, and store materials. They typically occupy space for predefined time intervals and move through the site in various patterns based on the type of their work and the material involved. Workspace is the 3D physical space needed to cater for a resource, characterized by its shape and volume, and governed by material quantities, dimensions, shape, and stacking ability (Riely & Sanvido, 1995; Riley & Sanvido, 1997). The common practice is to represent a workspace by a 3D bounding volume which can take different forms such as a bounding box, a bounding sphere, an oriented bounding box, an axis aligned bounding box (Choi et al., 2014), a rectangular box (Dashti et al., 2021), or a cylinder (Rohani et al., 2018). Another practice is the cell representation where the site layout is represented by a grid of numerous interconnected cells; this representation is mainly used for moveability analysis (Wang et al., 2019). A work envelope is defined as a 3D space volume enclosing a building component, and allowing a construction worker to be there and perform a construction task on this component, along with corresponding equipment and material (Bannier et al., 2016). Rohani et al. (2018) consider a transparent cylinder with a base area of 3.14 m^2 and a volume of 5.5 m^3 for representing the workspace needed by a static man-hour. Moreover, research has constantly revealed that productivity decreases when the threshold of one worker occupying 28 m^2 is crossed (Riley & Sanvido, 1997) . Su and Cai (2014) distinguish between two aspects to consider in workspace planning, namely workspace structure and the method of geometric modelling. The workspace structure determines the way the workspaces are arranged to correctly represent a construction task and the way they are managed for project participants to access the required information. As for the method of geometric modelling, it indicates how to generate workspace geometries.

OVERVIEW OF WORKSPACE PLANNING METHODS

Tommelein and Zouein (1993) presented MovePlan as a 2D interactive dynamic layout planning model. It is a construction schedule augmented with data required to establish layouts, such as resources and their dimensions, and which positions temporary facilities and movement of material and equipment on site. The model output can be additionally refined by integrating geometric detail and advanced graphical packages. Akinci et al. (2002) presented a mechanism for automating the process of generating workspaces and creating a space-loaded production system. Superintendents were asked to describe the workspaces needed generally based on the construction method they are intending to use. Such generic descriptions address the size and position of every workspace qualitatively as being oriented with reference to an object. Dawood et al. (2005) developed the virtual construction site (VIRCON) as a set of assisting tools for project planners to do informed and accurate planning decisions when allocating activities' execution spaces. However, several limitations were noted with the developed system, such as lack of visual representation of spatial overload simultaneously with the project plan, difficulty in allocating space, not being user friendly, and need for manual optimization. Spatial overload occurs when the aggregated space demand matches or exceeds available space. Su and Cai (2014) tackled workspace planning and modelling via a life-cycle approach. The study investigated workspace evolution patterns through an object-oriented data structure. Different life cycle stages of a task are identified along with corresponding needed workspaces which are then arranged into sequences. The developed model proved to be more accurate than models with single workspace representation. Moradi et al. (2015) developed a 4D-BIM system to dynamically detect spatial-temporal conflicts and quantify the corresponding impact on project performance. A workspace is generated and assigned by identifying four parameters which are orientation, width offset, length offset, and extension value. The proposed model allows more accurate detection of conflicts and determination of conflict severity. Kumar and Cheng (2015) presented a framework that makes use of BIM in creating dynamic layout models for construction sites. This is done through estimating the dimensions, size, and number of interim facilities needed at various stages of construction. Their results show through a demonstrative example that the developed model could achieve 13.5% reduction in travel distance as compared to traditional methods. Bannier et al. (2016) presented a framework for integrating information pertaining to work envelope needs among the steel and piping trades in order to support space planners during preconstruction phase. Superintendents on industrial projects were interviewed to define conventional work envelopes. Their results showed that the anthropomorphic characteristics of a population considerably affects work envelope requirements. Mirzaei et al. (2018) presented a 4D BIM model that dynamically detects and quantifies spatial temporal conflicts and their effect on project performance. The crew movement is taken into consideration by simulating four different execution patterns with four distinct starting points. Workspace planning is also looked at from a safety perspective. For instance, Choe and Leite (2017) developed a 4D planning process for construction safety that considers site-specific spatial and temporal information. Their findings revealed that risky zones, activities, and days could be prioritized when information relating to number of workers, occupation type, and zoning plan is included in project schedule.

All that being said, workspace planning studies mainly address building construction and are scarce for industrial construction.

CHALLENGES WITH WORKSPACE MODELLING

Dynamic workspace modelling is faced by two major challenges during construction planning, which are modelling the workspace's geometry and capturing its accurate dynamics. The term "workspace dynamics" simply refers to the dynamics occurring from change in geometry to position of workspaces across time. Since an activity can occur at different locations throughout different stages, one workspace falls short of representing such progressive series of workspaces. Moreover, each task impacts the workspace differently. For instance, a slab construction task increases the floor area as construction progresses, whereas a drywall construction task divides or partitions the existing space into reduced units (Riely & Sanvido, 1995). Commonly, actual workspace variations go unnoticed in planning and even in control (Wu & Guo, 2014). Figure 1 illustrates an example based on Riely and Sanvido (1995) of how a construction site constantly changes with time. Beginning at time t, no construction work takes place. After a while at time $t1 > t$, a slab construction task is in place. Further ahead at time $t2 > t1$, masonry works take place which encloses the space and reduces access. Finally, at time $t3 > t2$, drywall installation task occurs, altering the site layout. Failing to consider the dynamic progression of workspaces reflects negatively on planning as it may yield imprecise information to planners (Su & Cai, 2014). Another challenge is that generally, people who are given the task of space planning, such as field engineers or superintendents, might lack the skill and knowledge of assessing the precise geometric parameters of workspace needed by each task. Especially in industrial projects, academia efforts pertaining to identifying and representing the piping activities' workspaces are scarce (Bannier et al., 2016). In other words, research focusing on extracting and translating the semantic information relating to workspaces from superintendents is still behind.

Poor space planning will eventually lead to overlaps in workspaces among various trades and to workspace clashes, resulting in potential safety hazards and congestion that impacts productivity and creates waste (Hammad & Zhang, 2011; Mallasi, 2006). Research showed that congested workspaces suffer losses in productivity amounting to 65% and delay in project duration reaching 30% (Hosny et al., 2020). Moreover, people not abiding by the workspace allocated for them creates issues. For instance, at times, project participants such as individual subcontractors set up their temporary storage areas, causing obstructions to other subcontractors. Another example of bad practices is leaving shelves and other products in space and having to relocate them several times which adds to transport and waiting times (Binninger et al., 2018).

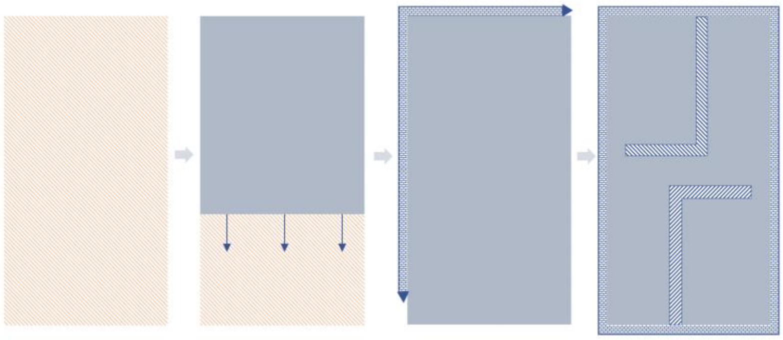

Figure 1: Evolution of workspace with time

FINDINGS: COMPONENTS OF WORKSPACE PLANNING

This section presents the main components required, but not exclusively, to formulate a workspace planning system as found in the literature. The first sub-section lists the different flow types in construction, followed by discussions on area patterns, workspace classification structure, conflict identification, and finally conflict resolution studies.

FLOW TYPES

When modelling workspaces on construction sites, it is integral to first identify all the entities that may occupy or "flow" within the workspace at any point in time. The verb "to flow" herein means "to move freely and continuously" as per the definition quoted by Kalsaas & Bolviken, (2010) and later adopted by Tommelein et al. (2022). Tommelein et al. (2022) distinguishes different types of flows in construction as depicted in Figure . Most studies focus on workflow, worker flow, and trade flow (Hosny et al., 2020; Kassem et al., 2015; Mallasi, 2006; Moon et al., 2014; Rohani et al., 2018; Su & Cai, 2014). A less number of studies considers additionally material, equipment, and tool flows (Choi et al., 2014; Dawood et al., 2005; Guo, 2002). As for the remaining flow types, they are mostly disregarded. Generally, each flow type gives rise to a specific pattern for workspaces, prefabrication areas, storage areas, and product space areas which are explained in the following sub-section. Also, each flow type might need specific workspaces. A workspace classification structure in presented in the sub-section following the area patterns.

AREA PATTERNS

Space behaviour patterns refer to the way a crew typically moves in a space across time to execute work elements. Such behaviour must be modelled to identify the links between tasks with distinct patterns and to forecast the workspace needed for task work elements. Riely and Sanvido (1995) distinguished between four area patterns which are work area, prefabrication area, storage area, and product space patterns.

A work area pattern refers to the directions and locations where different work units are achieved for various tasks and materials. An example is following a linear pattern to perform ductwork and install conduit. A prefabrication area pattern describes positions of prefabrication areas on site that are needed for different tasks or types of material. An example of such an area pattern is having one prefabrication area per floor for conduit assemblies. A storage area pattern refers to locations where material is kept from the time it is delivered until the time it is used. An example is having bulk storage where material is stored in a single location per floor, then distributed to work areas as required. Finally, product space pattern describes the impact that completed work will have on the existing space for upcoming tasks. An example pattern is creating space for following activities such as slab construction. A direct impact is when work resulting from a task directly conflicts with space required by other tasks, generating thereby sequential dependencies between the tasks. If a task is completed without putting into place material that directly impacts the available space for upcoming activities, then the result is no impact (Riely & Sanvido, 1995).

Figure 2: Flow types in construction based on Tommelein et al. (2022)

WORKSPACE CLASSIFICATION STRUCTURE AND GENERATION PROCESS

Understanding the structure and function of a workspace is crucial for proper workspace modelling. Table 1 is compiled based on a study by Choi et al. (2014); it provides a workspace classification structure that can be used in formulating a workspace modelling system. A workspace can be classified as direct or indirect based on its function. For instance, a workspace is said to be direct when it is associated in a direct way with activity execution such as workspace for installing a window. Object space (product), working space (working, tool and equipment), and storage space (staging) are classified as direct workspaces. An indirect workspace is either indirectly related to the execution of an activity or is needed for execution of several activities such as a corridor for personnel path. Unavailable space (hazard, protected), set-up space (unloading, layout, prefabrication), and path space (debris, personnel, material) are all indirect spaces. Furthermore, a workspace is categorized based on its moveability which can be fixed like window installation workspace or flexible like storage areas. Various considerations play a role in determining the size and location of a workspace; such considerations include the components' geometric features, construction method, management plan, facility layout, etc. Finally, workspace generation and expiration follow certain rules as Table 1 shows. Generally, generating a workspace requires three steps. The first step is to determine a task necessary for constructing an element or product. The second step consists of identifying individual workspaces required in each stage of the task's life cycle. The third step calls for associating the identified workspaces with the product or element (Su & Cai, 2014). By assigning precedence relationships between the generated workspaces, a standardized sequence of workspaces can be attributed to each construction task.

Table 1: Workspace classification structure based on Choi et al. (2014)

Type	Function	Movability	Size & Location	Generation	Expiration
Direct space	*Object Space:* Product	Fixed	Determined by components' geometric features	At activity's starting point of activity	Until completion of project
Direct space	*Working space:* Working Tool, equipment	Fixed	Determined by construction method definition of spatial relationship with object	At activity's starting point	At activity's ending point
Direct space	*Storage space:* Staging	Fixed or flexible	Size determined by material's quantity and geometric features, Location determined by material management plan	At activity's starting point	At activity's ending point
Indirect space	*Unavailable space:* Hazard Protected	Fixed	Determined by protection condition of object and construction method's definition of hazardous condition	Preserved through activity duration or protection duration controlled by feature of object protected	
Indirect space	*Set-up space:* Unloading Layout Prefabrication	Fixed or flexible	Determined by temporary layout of facility	At activity's starting point	At activity's ending point
Indirect space	*Path space:* Debris path Personnel path Material path	Fixed or flexible	Min height and width of path determined by activity's construction method and material's geometric features	During duration of activity	

SPATIAL-TEMPORAL CONFLICT IDENTIFICATION AND EVALUATION

When a workspace overlaps with another or more during construction, a dynamic short-term clash called a spatial-temporal clash occurs. Site planning, project features, management concerns, logistic and resources, and external environment are all categories of potential reasons causing workspace conflicts (Hosny et al., 2018). A variety of tools are proposed in the literature to detect and evaluate spatial-temporal conflicts as summarized in Table 2. The early research used sketches to visualize conflicts. With the advancement in CAD systems and virtual reality modelling, conflict visualization became easier, and more aspects were added to the analysis such as cost. A conflict is mainly evaluated with respect to its severity which is calculated by assessing overlapping areas ratios, overlapping durations ratios, required and available spaces ratios, etc.

Table 2: Conflict visualization and evaluation

Study	Tools for visualization	Conflict Evaluation
(Zouein & Tommelein, 2001)	Sketch	-
(Guo, 2002)	2D CAD	$ISP^4 = \frac{interference\ space\ size}{original\ size} \times 100$ $IDP^5 = \frac{interference\ duration}{original\ duration} \times 100$
The VIRCON project (Dawood et al., 2005) (Winch & North, 2006)	2D CAD 4D-CAD (3D CAD models + time) 4D Virtual Reality Modelling Language (VRML) format	$Spatial\ loading = \frac{required\ space}{available\ space} \times 100$
(Mallasi, 2009)	4D-CAD and VRML	Geometrical adjacency algorithm
(Chavada et al., 2012)	5D (BIM + time + cost)	$CS^6 = \frac{conflicted\ duration}{current\ activity\ duration} \times 100$
(Moon et al., 2014)	4D-CAD (BIM)	$WCR^7 = \frac{adjacency\ distance}{expanded\ interval\ distance}$
(Kassem et al., 2015)	4D	$CS = \frac{conflicted\ duration}{current\ activity\ duration} \times 100$
(Rohani et al., 2018)	5D-CAD	-

SPATIAL-TEMPORAL CONFLICT RESOLUTION STRATEGIES

Whether planners develop schedules first and then resolve any identified spatial conflicts (i.e., follow a reactive approach) or attempt to directly generate conflict-free schedules (i.e., follow a more proactive approach), a set of commonly used conflict resolution strategies have been identified based on a review of relevant literature. Table 3 summarizes these strategies and highlights the ones considered or discussed in each of the reviewed studies. As suggested by Rohani et al. (2018), these strategies could be generally classified into two categories; The first category includes strategies that help resolve spatial conflicts without impacting the total project's duration and cost and, hence, can be considered less intrusive. Examples of such strategies include modifying the direction of work execution (e.g., north to south instead of south to north) or modifying activity start time within its float time. It is important to note, however, that even though certain strategies that are typically classified under this category may not have a direct impact on the project's duration or cost, they may have an indirect effect. For instance, modifying space size has been thought not to affect the schedule's critical path (Chavada et al., 2012) or the direct/indirect costs of the project (Rohani et al., 2018). However, reducing the size of a workspace may adversely affect the productivity of the corresponding activity (Guo, 2002), which, in turn, may lead to increased project's duration (if the activity is

[4] Interference Space Percentage
[5] Interference Duration Percentage
[6] Conflict Severity
[7] Workspace Conflict Ratio

critical) and cost. Hence, when selecting strategies to resolve spatial conflicts, careful consideration of their potential consequences must be taken even if the strategies are deemed non-intrusive. The second category includes strategies that are more intrusive and likely impact the project's duration and cost. Modifying the number of resources assigned to a critical activity in order to reduce the number of space users is one example of such strategies. Plainly, researchers recommend resorting to the second category only when certain spatial conflicts cannot be resolved using the first category strategies.

Table 3: Conflict resolution strategies

	Strategies \ Studies	(Zouein & Tommelein, 2001)	(Guo, 2002)	The VIRCON project (Dawood et al., 2005)	(Winch & North, 2006)	(Mallasi, 2009)	(Chavada et al., 2012)	(Moon et al., 2014)	(Kassem et al., 2015)	(Rohani et al., 2018)
1	Modify/delay activity start time	✓	✓	✓	✓		✓	✓	✓	✓
2	Modify resource allocation (i.e., number of space users)	✓	✓	✓	✓	✓			✓	✓
3	Modify space location		✓				✓		✓	✓
4	Divide the original space into multiple smaller spaces		✓							✓
5	Modify activity duration		✓	✓	✓		✓			✓
6	Split activity		✓							✓
7	Modify activity sequence		✓						✓	✓
8	Modify space size		✓				✓		✓	✓
9	Store idle resources off site	✓								
10	Modify execution direction					✓			✓	✓
11	Modify the construction method		✓				✓			✓

CONCLUSION AND ADDITIONAL CONSIDERATIONS FOR WORKSPACE PLANNING

The common practice in construction is to create schedules then resolve spatial-temporal conflicts. Workspace planning has not achieved diffusion in practice, especially in industrial projects that face lack of academia efforts in this regard. This paper presented a narrative literature review on workspace planning and summarized major findings from leading research studies. The study offers an overview of the existing workspace planning methods, challenges faced with workspace modelling, and general components that form the base for workspace planning such as flow types, area patterns, classification structure, and conflict identification and resolution. Moreover, this study offers below general considerations to examine when developing a space planning system. One thing to note is that a construction project goes through various phases from feasibility studies to construction, and operation and maintenance. Each phase is characterized with a distinct level of development (LOD) for the 3D models and project schedules. Such LODs strongly impact the 4D simulation's purpose and quality. Guidelines for defining and selecting LODs appropriate for project needs and progress are discussed further in a study by Guévremont and Hammad (2020). The considerations are:

- What is the level of abstraction sought? What is the unit of analysis: project level, industry level, company level, team level, area level, etc.?
- What LOD the system will tackle?
- What level of complexity can the system handle?
- What types of flow will the system consider?
- Who will use the system (i.e. foremen, superintendents, planning engineers...)?
- What will the system look like to help engineers better manage the space?
- How to align the system with the Last Planner System (LPS)?
- What kind of simulation is most suitable for the type of projects at hand?
- How to perform solution evaluation of the developed system?
- How to integrate BIM with the model?
- What input should be included in the system?
- How to define the parameters required for the system?
- What templates are suitable for accommodating the modelling process?

Finally, some limitations are associated with this study. First, the paper is based on a narrative literature review, which means that the results are limited to the studies and sources that were included in the review. Therefore, the findings may not represent the complete picture of the field of workspace planning. Second, the paper provides general considerations for developing space planning systems, but it does not provide a detailed framework or methodology for implementing such systems. Third, the paper mentions the Last Planner System (LPS), which is a production planning and control system used in construction projects. However, it does not provide sufficient information on how to align space planning systems with LPS. In conclusion, if we can accurately assess the space requirements, patterns, and impacts of each task on the construction site, we can simulate different plans and generate optimized, conflict-free schedules. This research advocates taking a step back to look at planning from a different perspective, and then adopting the general considerations presented as a guide to develop space planning systems that meet the specific needs of each project.

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A SYSTEM DYNAMIC MODELLING APPROACH FOR INTEGRATED LEAN-BIM PLANNING AND CONTROL METHODS

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ABSTRACT

Traditional planning and control methods do not accurately reflect the construction reality and lack feedback loops. The Last Planner System (LPS) and Location-based Management System (LBMS) have been suggested as socio-technical systems to generate practical and actionable real-life data based on production theories and logic. This data can be effectively communicated, analysed, and managed using the capabilities offered by Building Information Modelling (BIM) workflows. However, a true integration between Lean Construction-BIM is not yet matured, where parallel use of both concepts is still more common. This paper presents a conceptual framework based on a system dynamic modelling approach to elaborate a causal loop diagram (CLD). The CLD explores the interactions between basic management functions and waste, on this basis this paper proposes how the integration between LPS, LBMS, and BIM can be harnessed to apply waste elimination strategies. The results of this study can be applied as lean policy analysis for new lean adaptors to understand the impact of Lean-BIM for planning and controlling various wastes across the construction supply chain.

KEYWORDS

Last Planner System, Location-Based-Management, System Dynamics, Casual Loop Diagram, Building Information Modelling, Construction Waste

INTRODUCTION

The construction industry is highly fragmented, has low productivity, and is a slow adopter of new techs. Most construction projects are waste-prone, resulting in delays, defective products, accidents, material waste and cost overruns. The production is traditionally managed, which relies on ad hoc decisions directing site activities with low-resolution and unreliable plans without channels for feedback from downstream players, therefore encapsulating production tasks in black boxes (Sacks et al., 2018). That challenges the construction stakeholders to extract useful and reliable information on a weekly and daily basis about the production.

About 54% of root causes of project delays and poor productivity are attributed to unreliable planning and control Ballard & Howell (1998). In Koskela's (1992, 2000) theory of the Transformation-Flow-Value (TFV), it is explained that these inefficiencies are attributed to the Transformation (T) view because it hides the propagated waste across the construction supply chain and ignores the value chain between project actors and the final customer hence suggesting the Flow (F) and the Value (V) views to complement the T view. The Flow (F) view

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is an essential concept in lean philosophy that decomposes the construction processes into Value-Added (VA) and Non-Value-Added (NVA) activities (i.e., work-in-progress, rework, defects, unfinished products, and waiting) (ibid). At the same time, the Value perspective stresses the importance of actively pulling requirements from the final and internal customers to avoid non-value activities.

A practical implementation of the F is planning and control systems, namely, Last Planner System (LPS) and Location-Based Management (LBMS). LPS is a socio-technical system that increases the planning resolution collaboratively to shield downstream from the upstream variability (Ballard, 2000). LBMS is a technical Flow-based method that calculates forecasts, production rates, quantities, and resource consumption for each task and trade according to their physical location (Kenley & Seppänen, 2010). Both systems complement each other in attempting to bring the production problems to the surface by targeting continuous, reliable, and one-piece flow (Seppänen et al., 2010). The combination of both systems could establish production planning that addresses bottlenecks through structuring, sequencing, managing handoffs, and visualising the construction flow, and proactive control that aims at identifying, analysing and removing constraints while alerting people about potential interference in the production system (Seppänen et al., 2015). That would increase production flexibility and credibility through detailed, measurable, reliable, and stable plans (Frandson et al., 2014).

Construction production is information intensive, and planning accuracy requires consistent information models which can be accessed across organisation boundaries. Building Information Modelling (BIM) is a visual, computational, and analytical process that enhances the communication of integrated production information (process and product) (Dave & Sacks, 2020). According to the LC-BIM matrix provided by Sacks et al. (2010), 56 positive interactions could support value and waste elimination concepts. The application of LPS becomes potent by incorporating automated BIM workflows where decisions and feedbacks rely on information streamlined from BIM models during performing constraint analysis, task definition, sizing, and sequencing (Gerber et al., 2010). The development of software as a service and tools based on LPS-BIM is growing as an independent research area; examples of provided prototypes are KanBIM (Sacks et al., 2010), VisiLean (Dave, 2013), LPS-based BIM (Heigermoser et al., 2019), and Beam! (Schimanski et al., 2021). The application of LBMS requires BIM workflows to perform and manage extensive calculations of quantities, durations, resource consumption and production rate (Kenley & Seppänen, 2010). A commercial example of this integration is presented in Vico software which automates LBMS logic using BIM functionalities and extends 4D logic from CPM to LBMS (Trimble, nd).

Conversely, the current BIM solutions did not fully integrate LPS and LBMS functions. Instead, they are performed in parallel, which misses the full potential of both planning and control systems. Also, no research discussed construction waste explicitly using the three concepts. Therefore, this paper provides Casual Loop Diagram (CLD) to illustrate the waste propagation across a construction production system based on the work of Formoso et al. (2015, 2020) and then proposes a conceptual framework that applies LPS, LBMS and BIM to tackle the construction wastes. The first two steps of the SDM method are to define the research problem and conceptualise this problem using CLDs, which will be the focus of this paper.

The subsequent sections are structured as follows: a brief literature review on construction wastes, an explanation of LPS and LBMS, and a discussion of the existing BIM functionalities for planning and control purposes. The next section presents CLD for waste networks combined with functional areas of lean-BIM for planning and control. The final sections discuss the research contributions and conclude this paper's major elements.

LITERATURE REVIEW

CONSTRUCTION WASTE

Construction waste is a high-level concept that hinders productivity and incurs capital loss which is challenging to measure systematically (Formoso et al., 2020; Viana et al., 2012)—causing massive negative impacts on environmental, economic, and social dimensions. According to Horman and Kenley's (2005) meta-analysis, 49.6% of construction operations are NVA (Non-Value Adding) activities. The literature has approached construction waste using various definitions, including rework (Love and Li 2000), product defects (Josephson and Hammarlund 1999), re-entrant flow (Sacks et al. 2017), transportation (Belayutham, González and Yiu, 2016), and institutional waste (Sarhan et al. 2017). This disparity in waste measures shows that it is challenging to formulate a holistic framework and attempt to complete an analysis of the root causes of construction waste (Formoso, Bølviken, and Viana 2020).

The construction waste propagates in complex networks. Those cycles can be modelled using causal loops that relate wastes in unidirectional and bidirectional ways. The propagation of waste cycles inherits the same properties of construction processes (i.e., pooled, sequential, or reciprocal) (Koskela et al., 2013). Also, waste can be understood as discrete (task-level), synergistic (project-level) and systematic (organisational and contractual level) (Fernández-Solís & Rybkowski, 2012). Formoso et al. (2020) categorised the construction waste into previous stages (design, planning and control, material supply, and training); production wastes (quality deviation, making-do, transportation, waiting, work-in-progress; inventories), and terminal waste or traditional waste metrics (rework, defects, material waste, safety issues, gas emissions). The literature shows various similarities in taxonomies of production waste, but it is difficult to grasp their applicability without a series of case studies to provide a holistic view.

THE LAST PLANNER SYSTEM© (LPS)

The LPS is the most applied from LC methods; sometimes, the LPS term is used interchangeably with LC. The key goal of LPS is to shield downstream from the upstream variability to increase planning reliability and workflow stability (Ballard, 2000). The second feature is providing commitment planning which focuses on facilitating conversation between planners to identify activities, their sizes, sequence, and related constraints. The third feature is to increase planning details based on Kanban planning; LPS breaks down the construction planning into four to five stages, namely master planning, phase planning, look-ahead planning, weekly planning, and learning, as illustrated in Figure 1. LPS uses social-technical measures that steer people to communicate project activities in detail with their constraints and requirements. Through a higher level of planning detail, planners can filter and pull ready (non-constraint) activities from the collaboratively developed backlog. The control function of LPS is enabled through PPC (Plan Percent Complete) and RNC (Reasons for non-compliance) metrics. They can be used to track the construction's progress and constraints to production—examples of analysis methods that can be used are 5whys and A3.

	SHOULD	CAN	WILL		DID
Planning Stage	Master	Phase (Pull)	Lookahead	Short-term	Learning
Planning Window	Milestones	Phases	4-6 weeks	Weekly/Bi-Weekly/Daily assignments	
Planning detail	Rocks (Milestones)	Rocks (Phases)	Boulders (Processes)	Pebbles (Operations)	Pebbles (Assignments)
Main activities	• Define key milestones • Identify critical path (CPM) • Assign start-finish relations	• Apply reverse planning • Identify handoffs, durations, and overlaps • Define delivery conditions	• Constraint analysis • Breakdown Processes • Design for operations	• Make reliable promises	• Measure PPC* • Investigate RNC** • Standardize
Addressed wastes	• Budget overrun • Schedule overhead • ENV measures • Value measures • Defects	• Budget overrun • Schedule overhead • ENV measures • Value measures • Defects	• Making-do • Work-in-Progress • Inventory • Crews absent, injuries • Transportation • Information delay • Rework	• Idle (waiting) • Unfinished works • Rework • Moving	• PPC Failures
Actors	• Owner • Portfolio Managers • Project Managers	• Project Managers • Site/production Manager	• Project Managers • Site/production Manager	• Project Managers • Site/production Manager • Crew managers	• Project Managers • Site/production Manager • Crew managers

*PPC = Plan Percent Complete; RNC = Reason for Non-Compliance

Figure 1: The structure of LPS stages, related activities, addressed wastes and actors.

LOCATION-BASED MANAGEMENT (LBMS)

LBMS is a system of preplanning, planning, scheduling, and controlling production according to units of physical locations. That is based on locations by calculating the quantity of work to be accomplished and the production rate (Kenley & Seppänen, 2010). LBMS breaks down the project into Location Based Structure (LBS), using the same Work Breakdown Structure (WBS) logic but applied to physical locations (Kenley & Seppänen, 2010). LBS divides the project into interdependent structures that can be built separately and narrowed to manageable locations where one trade can operate continuously without waiting. According to LBMS logic, reducing the interdependencies provided by CPM, removing float between tasks, and synchronising production rates is possible. The control indicators applied in LBMS can forecast production capabilities and provide information about the root causes of cascading delay (i.e., work-in-progress, waiting, rework, and congestion) (Kenley & Seppänen, 2010). LBMS reduces production complexity by streamlining continuous flow across location, which steers planning targets towards stable and interrupted production, gives clear directions for trade crews, and reduce trade risk and waiting time (Biotto & Kagioglou, 2020).

REFLECTION ON LPS AND LBMS

Although the wide acceptance of LPS, many gaps have been reported regarding PPC metrics, automation level, and cost management. Firstly, PPC does not measure or reflect any flow parameters, such as variation in production rates, trade discontinuities, out-of-sequence work, product CTs, WIP levels, bottleneck production rates, and levels of non-value-adding work (Maraqa et al., 2021). That can be partially addressed using LBMS, which provides metrics of flow quality, and actual flow line charts, which show the locations, and the movement of trade crews across spatial-temporal dimensions (Maraqa et al., 2021). However, focusing on productivity metrics offered by LPS and LBMS can lead to counterproductive behaviour by steering the production towards results instead of managing by means. Secondly, a major gap shows that LPS and LBMS are still lagging in supporting real-time flow monitoring, which is a challenging lack of automation, as Ratajczak et al. (2017) indicated. Thus, adopting more tracking and tracing technologies, such as IoT sensors, is envisioned for autonomous data entry for BIM-based production planning and control systems (Dave et al., 2016). Regarding the cost management function, there is little evidence of cost control supported by LPS (Schimanski et al., 2021), which can be complemented by the measures supplied by LBMS in calculating quantities, resource consumption and production rates.

BUILDING INFORMATION MODELLING

BIM becomes a de facto technology in AECO industries which brings various actors to use a shared digital representation of a built asset to facilitate design, construction, and operation processes to form a reliable basis for decisions (ISO, 2018). BIM functionalities can overcome major information problems such as design inconsistency, errors, and duplications caused by conventional design workflows (Sacks et al., 2018). Successful implementation of BIM stands on three pillars, process, people, and technology (Hardin & McCool, 2015). Lean construction can complement the former two pillars, while the latter relies solely on extensions to the existing BIM functionalities. These functionalities include parametric modelling, interoperability, clash detection, 4D simulation, functional analysis, and documentation (Sacks et al., 2018). Thanks to interoperability functionality, it is possible to seamlessly exchange design information between different BIM systems and design speciality (e.g., by Industry Foundation Classes (IFC)) (Sacks et al., 2018). 4D planning encourages discussion of several plan alternatives, increases process transparency, and improves planning reliability (Bortolini et al., 2019).

However, 4D planning is not fully exploited in production planning (Schimanski et al., 2021) because short-term planning is not considered in commercial 4D planning (Ardila & Francis, 2020), which is mainly programmed for documenting and analysing production plans according to activity-based logic. Thus, most BIM solutions are not fully developed for lean data processing; instead, they are used in parallel with LPS and LBMS (Schimanski et al., 2021). Therefore, lean planning and control systems and BIM integration exist, but their full potential is not realised yet.

RESEARCH METHODOLOGY

This study aims to enable lean stakeholders to identify the effect of LPS, LBMS and BIM on waste elimination by micro-mapping objects and spaces using the Casual Loop Diagram (CLD) according to the theory of System Dynamic Modelling (SDM). The SDM measures the effect of change in a system over time with a high level of abstraction and minimum level of detailing. SDM was coined in the 1950s by Jay Forrester to depict the change in socio-economic systems' behaviour over time as a broad evolving methodology to conceptualise, describe, analyse, and manage feedback systems (Sterman, 2002).

Figure 2 illustrates the research methodology used in this paper, representing four steps of developing SDM. The scope of this paper is to conceptualise the problem (step 1) by formulating a Casual Loop Diagram (CLD) for production wastes and construction management functions (including material delivery, production planning and control, site layout planning, and product design using BIM). CLD can explain the dynamic hypothesis by visualising a complex system's cause-and-effect relationships between variables. Constructing a CLD involves six activities 1) research question definition, 2) variables identification, 3) links between variables, 4) polarity identification, 5) assigning feedback loops, and 6) determining delays (not included in this paper). The main use of CLDs is communicating with stakeholders and constituting a framework that captures expert knowledge, and a main drawback of SDM is that a high level of abstraction works with averages that cannot be used at operational and tactical levels. Also, it has limited animation capabilities compared with Agent-Based Modelling (ABM) and Discrete Event Simulation (DES).

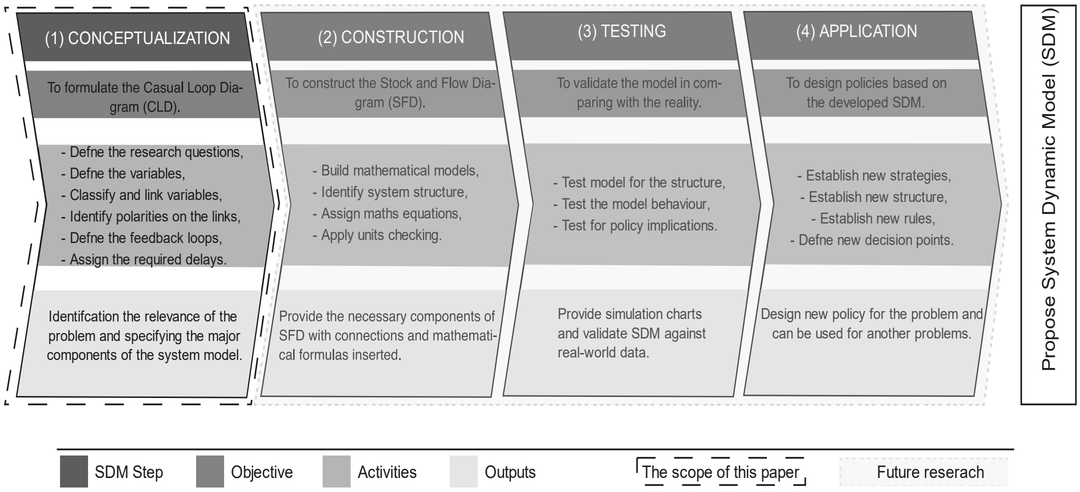

Figure 2: The research methodology

CAUSAL LOOP DIAGRAM (CLD) FOR WASTE ELIMINATION

CLD is a conceptual tool that shows dynamic and complex problems related to their solutions and reveals a chain of cause and effect. Such a diagram consists of a set of nodes representing variables connected, the relationship between these variables, represented by arrows, can be labelled at the arrowhead as either positive or negative. The CLD presented in 3 is based on (Formoso et al., 2015, 2020), who proposed a network analysis that could depict the patterns of the construction wastes by drawing links among taxonomies of wastes and between the construction waste and the production system stages. This CLD also adopts the components of Integrated Lean Project Delivery (ILPD) presented by (Ballard & Howell, 2003), lean design, lean supply, lean production planning and control. In addition, BIM processes and Quality management were added to the CLD to investigate the relationships between all mentioned concepts and production waste concepts. By analysing the diagram of Figures 3, the following loops can be clearly recognized:

Loop R1 highlights the effect of material delivery and site layout planning on the inventory, where inventory is a temporary facility that should be planned in the site layout. The more frequently delivered materials, the bigger inventory on site is needed when the resource consumption may not meet the delivery rate. Additionally, the more parts are delivered, the more complex inventory management is required to reduce inventory accumulation. Loop B2 concerns material waste as an outcome of damaged materials due to storage and movement, excess inventory, and rework. Other causes of material waste indirectly arising from Production Planning and Control (PP&C), for instance, improper allocation of materials, poor site layout plans, damage during transportation (as shown in Loop R4), poor handling, and improper material staging and among others (For more about material waste, check (Formoso et al., 2002). In loops B1 and R3, the labour movement across physical locations is affected by the material delivery, the routes and site layout design and planned activities by Production Planning and Control (PP&C). Information about labour routes across the physical locations can be scheduled and controlled through LBMS with the support of BIM for obtaining quantities and geometrical analysis for the site layout.

In loop R2, the PP&C actions about work are streamlined from collaborative efforts to prepare work to be structured, sized, sequenced, scheduled, communicated, and controlled, which appears to play a central role in the CLD PP&C is essential for releasing pull signals for the whole production system about crews' resources, production progress, resource consumption, production rates, constraints, etc. LPS and LBMS can provide this kind of information, which can be considered a real-life data generator about the production system, which helps stakeholders streamline informed decisions about production instead of traditional ad-hoc methods. A proper PP&C system should consider the role of variability in the production system (e.g., the parade of trades), where work chunks should be sequenced, and handoffs between trades should be negotiated and harmonised to prevent starvation or overproduction of planned tasks. As well as, PP&C has to provide proactive measures to eliminate the root causes of cascading delays (i.e., interference between the trades in tasks or locations can cause flow interruptions).

The impact of information availability is a prerequisite for PP&C functions, as well as this variable limit the likelihood of making-do emergence and request for information (RFI) (as shown in Loops R14 and R6). A well-defined BIM execution plan should match the Level of Development (LOD) with PP&C details. Information availability variables can be streamlined through tracking and tracing technologies such as indoor positioning, cloud points, and Internet of Things (IoT) techs. These provide real-time control for the construction site conditions that can be connected to the BIM process for further visualisation and analysis steps.

Several policies could be applied to regulate the effect of material delivery on project performance. On the site, by inserting measures of PP&C associated with planned site layout planning (SLP) (Cheng et al., 2015). These functions send ‘pull’ signals for materials to be timely ordered and delivered under the just-in-time (JIT) concept. In the PP&C, the materials should be quantified and allocated before execution. Thus, in any process that commences without the perquisite materials, a making-do waste arises, which is responsible for other wastes such as Work-In-Progress (WIP) and unfinished works and hinders labours' productivity. Another waste not communicated in Figure is substitution waste, a phenomenon that urges to substitute unavailable materials with other materials to meet schedule deadlines; this waste is similar to making do but hinders productivity due to reworks and defects.

The material delivery also impacts the reliability of production planning and control (e.g., when the required materials are not available when the planned work is released, a making-do effect could be raised, which can be snowballed to the emergence of rework and defects). The role of SLP (site layout planning) is necessary to coordinate physical locations between the demand of the production system and temporary facilities, delivered materials, crew movements, machine setups and truck traffic.

BIM processes positively reduce design changes, variability, rework and RFIs (Sacks et al., 2018), as shown in Loops R11, R12, and B4. BIM functionalities such as quantity-take-off, 4D planning, visualisations, clash detection, and interoperability are available in commercial software, bringing valuable information control to the PP&C systems. A true interaction between BIM functionalities and lean-based PP&C is not mature, the literature actively proposed different prototypes, but a real impact on waste elimination is not presented yet. However, the potentials of BIM functionalities' impact on waste reduction are evident even on final wastes such as rework, material waste, and capital waste.

B3, R9, and R10 concern the quality management to control variability using quality control charts and continuous improvement methodology based on the PDCA cycle (Deming, 1982). Construction variability is the main source of product defects and process discontinuity, leading to reworks, poor productivity, and eventually to, capital waste and cascading delays. Loop R7 illustrate the causality of Making Do with WIP and unfinished works. The impact can be explained by working on activities without its prerequisites (e.g., trades that focus on local optimisation are reluctant to pick the easiest available work packages at the beginning, “a low-hanging fruit phenomenon”, crews move to open spaces until a problem appears, leave unfinished work behind them, and prevents WIP to be progressed. Eventually, this phenomenon led to interruptions in workflow and interference with other trades' schedules, leaving labours to wait until the problem is resolved, where overtime strategy would be a solution to compensate for the delay, which can lead to labour fatigue and labour productivity to be negatively impacted

(Loop R8). Again, the impact of making-do waste is complex and cannot be modelled in a unidirectional causality link (Formoso et al., 2020), which contradicts CLD principles (As shown in loops R7 and R8, the link between making-do and unfinished-works is bidirectional). Thus further investigation is needed to explore intermediate variables between making-do and other wastes.

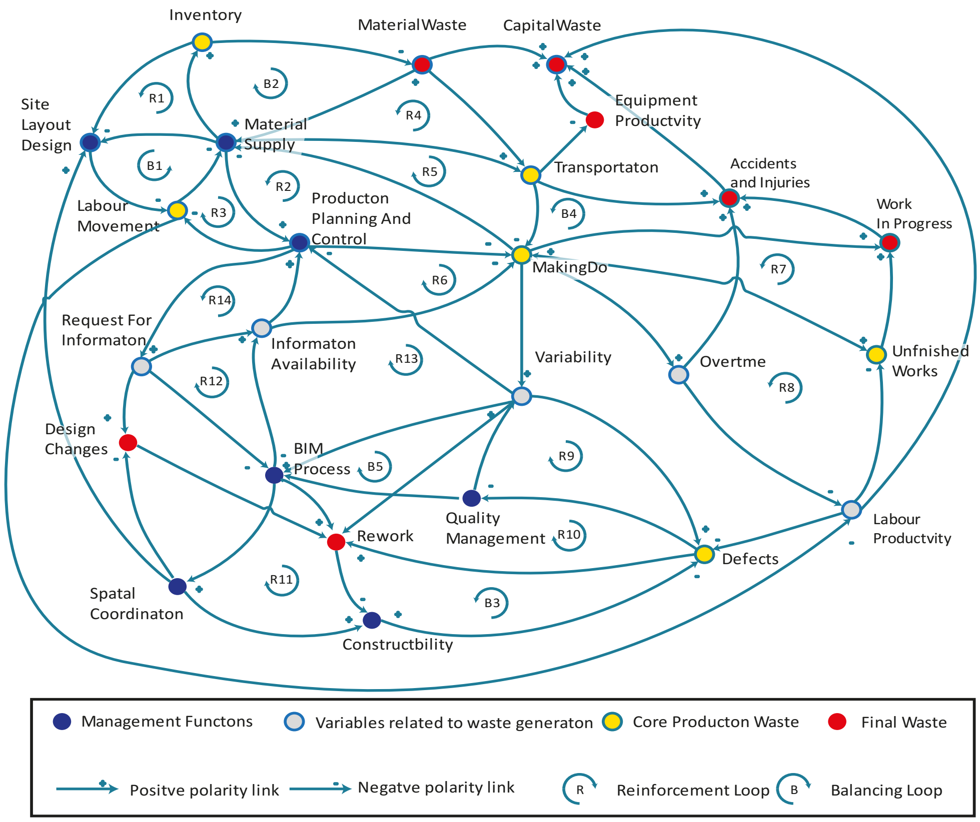

Figure 3: A CLD of wastes and production system functions adapted from (Formoso et al., 2020)

BIM-BASED INTEGRATED PLANNING AND CONTROL

BIM workflow is in the middle of the proposed framework in Figure 4 because BIM is considered as single truth source and because it supplies the necessary data for the variables governing LPS and LBMS (i.e., start and finish time, production data, geometry, and resource quantities). LPS can apply different scheduling methods, but this research applies LBMS forecasts for scheduling, planning, and controlling the production and alarms LPS stakeholders about upcoming and ongoing production problems, and supplies them with locations, crews' consumption (manhour/unit), production rates, and quantities (Kenley & Seppänen, 2010). While the site teams' feedback suppliy information about quantities, constraints and commitments during look-ahead planning and weekly planning (Seppänen et al., 2015). Thus, the deficiencies of LPS will be complemented using LBMS countermeasures (Tommelein & Emdanat, 2022).

During the master scheduling stage, milestones are determined, and the master schedule is defined using LBMS scheduling techniques. BIM is at schematic design, which approximates estimations, identifies main phases and primitive tasks, and provides geometrical analysis for defining a rough Location Based Structure (LBS). The outputs are milestones, phases, flow line schedule and Gant chart schedule. In this stage, high-level waste elimination can be targeted (i.e., capital waste, environmental waste, safety issues, rework and defect rates, and inventory). In phase scheduling, collaborative backwards (pull) planning from defined milestones in the master schedule is applied, where work chunks and handoffs can be determined without defining durations. LBMS functions are divided into scheduling and optimisation (Seppänen et al., 2010). The first targets the setting of LBS (i.e., units of equal size of work in locations that assures trades to work until they get work completed in a location before moving to another location). Collaboratively, LBMS also seeks optimisations in phase scheduling (including adding more resources, splitting tasks, accepting discontinuous work, decreasing crew size, and adding more scope) (Seppänen et al., 2015). The spatial coordination stage of BIM can provide 4D schedules for better visualisation and clash detection to identify the product systems interference. The aimed waste in phase scheduling are design changes, reduction of Request for Information (RFI), schedule overrun, movement, transportation, and defects.

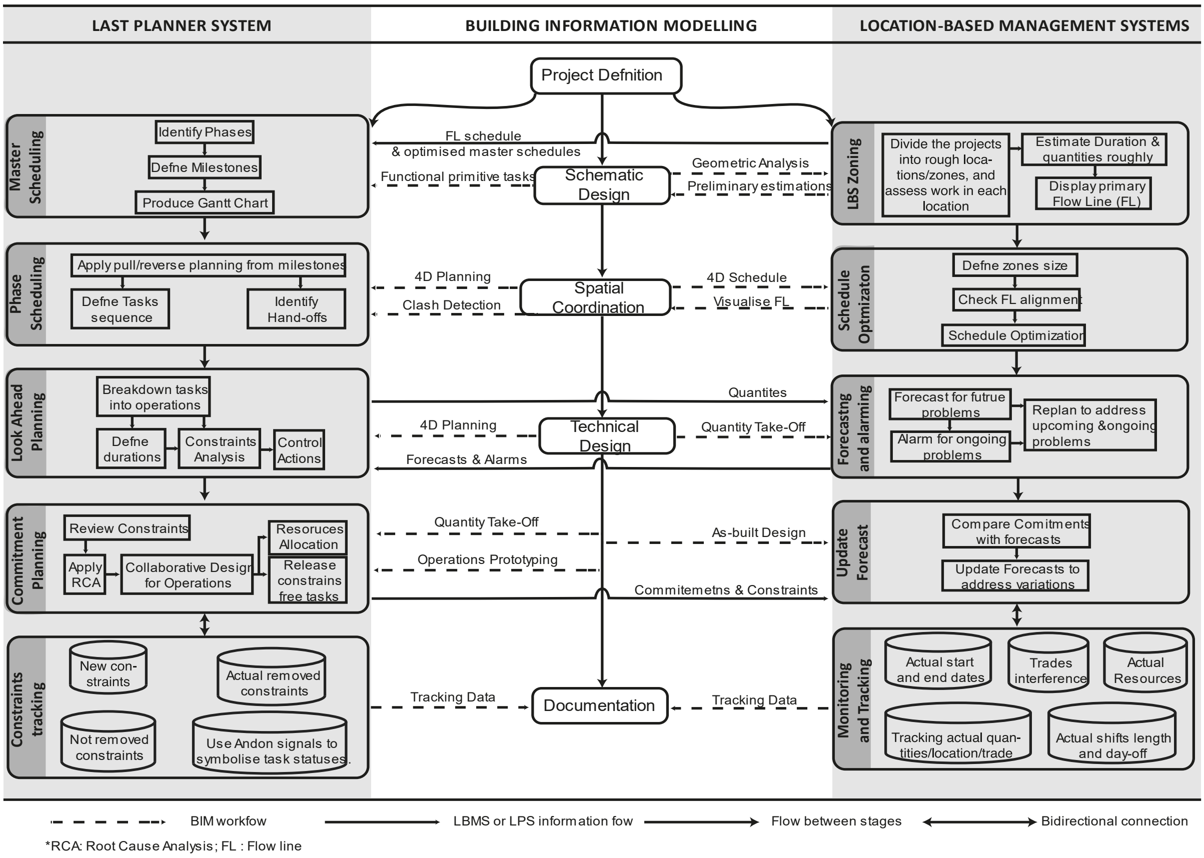

Figure 4: Assembled sub-systems of LPS, LBMS, and BIM.

The control functions commence with the look-ahead planning stage. A social process of LPS breaks operations into tasks, and a technical process of LBMS breaks operations into locations. In LPS, stakeholders apply constraint analysis to identify, diagnose, assign, and remove potential constraints for each task in a phase when durations are determined for each task. LBMS collects the required data about crew consumption, quantities, and production rates from trades, BIM take-off, and LPS. This information is used to forecast future problems and alarm ongoing production problems. Root Cause Analysis (RCA) is applied to seek systematic control actions that remove constraints supplied by LPS and mitigate the schedule risk provided by LBMS.

In the commitment planning stage, the LPS teams review the constraints and commitments in short-term windows. A collaborative effort is applied to design for operations, and the simulation functionality in BIM would be useful for providing prototyping at the operational level (Seppänen et al., 2015). At this stage, LPS functions are more applied than LBMS, but the LPS commitments are to be compared with LBMS forecasts to adjust exceeded plans (Seppänen et al., 2010). Finally, Production tracking is necessary to pull information from the site to planning and control systems, as shown in Figure . This function can detect the status of commitments, constraints, tasks progress, bottlenecks information, interference, actual resources, start and finish dates, shifts, and other quantities. The literature suggested various technologies to track and monitor the production information (e.g., (Dave & Sacks, 2020; Zhang et al., 2015). Tracking and monitoring function is essential to close the feedback loop of the suggested system, increase the situational awareness of trades and planners about the production, and bring management attention towards critical issues that generate waste and hinder value delivery.

CONCLUSIONS

This paper applied the System Dynamics theory to investigate the impact of production planning, control, and BIM on waste elimination. Based on a literature review, a Causal Loop Diagram (CLD) was illustrated to highlight the dynamicity of waste propagation and the interactions and feedback loops among BIM and planning and control functions. Then a generic framework was proposed to assemble the flows between Location Based Management System (LBMS), Last Planner System (LPS), and BIM. Waste measures should be used as guidance and actionable language when applying LBMS and LPS-based BIM. LBMS and LPS provide systematic, preventive, and proactive waste elimination measures from the early stages of the project, while BIM provides enormous data collection, analysis, and exchange on the elaborated wastes. By harnessing BIM functionalities, lean practitioners could communicate potential production wastes at different planning and control stages.

System dynamics may be viewed as the initial methodology to analyse waste accumulation across a specific timeline. Thanks to the clarity a dynamic system model provides, stakeholders can identify and resolve planning and control issues and measure the impact of countermeasures on waste elimination efforts. The combination between the LPS and LBMS in association with BIM functionalities streamlines powerful improvement for the construction production systems. Regardless of the ease of understanding, CLDs can be communicated with stakeholders with diverse backgrounds and experiences. The proposed CLD requires additional concepts, such as delays which enhance the system behaviour by adding waiting time measures when necessary.

Moreover, the elaborated CLD is limited because it is abstract and conceptual, which may not build a reliable judgement to be implemented on a real-world project. This paper is part of ongoing research that aims to model lean thinking using system dynamics. The future research will collect experts' views based on the case study research method on the elaborated casual loops diagrams and transform them into operable stock and flow diagrams, which allows the researchers to simulate the system by manipulating the model's major variables and compare runs among the different scenarios across a specific timeline.

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A MECHANISM FOR SMART CONTRACTS TO MEDIATE PRODUCTION BOTTLENECKS UNDER CONSTRAINTS

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ABSTRACT

Central project managers devote massive efforts to monitor, track, coordinate, and take actions to diagnose and prognose governed constraints and remove them to enable a reliable workflow. The blockchain-enabled smart contract can streamline the work process by predefining "intelligent" consensus to facilitate central managers' jobs. However, the inability of smart contracts to handle unexpected events under complicated environments posited challenges in realizing it automatically. This study aimed to develop adaptive mechanism to mediate production bottlenecks caused by constraints. First, the research identified the four main types of constraints and their levels of variability from a prefabricated project. Then, a simulation model was established to quantify the impacts of different constraints and determine the fair payment rules. Lastly, different constraint-bundled scenarios and execution policies were developed and encoded in the smart contracts for automated executions. Smart contracts can assist construction managers to motivate reliable production and minimize waste caused by bottlenecks in the system.

KEYWORDS

Constraint, simulation, smart contracts, Shapley value, modular construction

INTRODUCTION

This study aims to improve production flow by modeling potential scenarios integrated with smart contracts during planning to assist the team in making informed decisions that lead to a reliable flow. Enabling a reliable construction workflow requires timely identification and removal of constraints under dynamic construction scenarios (Javanmardi et al., 2020). Koskela (1999) identified that at least seven types of constraints must be removed during the planning stage: design and working method, components and materials, laborers, equipment and tools, space, prerequisite work, and external conditions. However, such a task requires central project managers to be proactive and increasingly detailed iterative planning actions to identify and

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remove constraints to make ready before the tasks are released into production (Sacks et al., 2020).

The recent advance of blockchain-enabled smart contracts showed great promise to streamline the construction process by infusing “intelligent” consensus in smart contracts to facilitate central managers’ jobs (J. Li et al., 2019; Mason & Escott, 2018). However, various research pointed out the difficulties of establishing such a consensus. For example, Hunhevicz et al. (2021) argued that complicated construction environments posited various uncertainties in smart contract executions. Therefore, ensuring the flexibility to handle unexpected events when designing smart contracts was crucial for successful implementation. Hamledari & Fischer (2021a) mentioned that smart contracts heavily rely on individuals who design the underlying consensus to enable its “smart” in automation. Nevertheless, Lu et al. (2021) stated that construction resources (e.g., workers, equipment, materials) could be turned into smart construction objects with properties of awareness, communicativeness, and autonomy to enable communications between the construction process and blockchain networks. Such a theory indicated the supporting flows (e.g., workers, equipment, materials) could be used as a “Check” mechanism in smart contracts to decentralize and enhance production. However, there are research gaps in converting intangible process-level constraints into tangible smart contract manageable consensus explicitly to enable automation and enhance the intelligence of a decentralized governance mechanism.

This study aimed to develop an adaptive smart contract by encoding constraints and quantifying their interactive relationships as management consensus. First, this study identified the four main constraints for a construction project and defined various levels of variabilities for each constraint. Then, a simulation model integrated with the Shapley value algorithm was developed with permutation and combination to quantify the impacts of different constraints and determine the fair payment rules. Lastly, different constraint-bundled scenarios and related payment policies were encoded in the smart contracts for automated executions. Test scenarios were generated to validate and verify the smart contract implementations. The developed smart contracts provide a solution to automatically handle dynamic constraint events with minimum central managers’ efforts. The developed smart contract prototype can be extended to model Koskela (1999)’s seven types of constraints with suitable adjustments to project needs.

LITERATURE REVIEW

CONSTRAINT MANAGEMENT

In construction management, Koskela (2000) developed a systematic transformation-flow-value (TFV) production theory to streamline the construction production process. Here, the transformation focuses on converting inputs to products; the flow theory emphasizes construction task, material, and information hand-offs; and the value theory stresses customer satisfaction. Specifically, the flow perspective treats production as flows of processes to improve their reliability and eliminate waste. Koskela (1999) suggested that at least seven types of constraints should be removed during construction planning: construction materials, tools and equipment, laborers, prerequisite work, design and working methods, space, and weather. While the constraints widely exist in practice, it takes construction professionals significant time and effort to identify and eliminate them to achieve the desired production pace and reliable workflow (Javanmardi et al., 2020).

In the past decades, it has been shown that constraint removal has a significant relationship with workflow reliability (Jang & Kim, 2008). Hamzeh et al. (2016, 2015) identified constraint removal during make-ready impacts construction lookahead plans and eventually affects project duration. Liu et al. (2011) further revealed a positive relationship between workflow reliability and constraint removal through a case study. In recent years, research was also developed to visualize various constraints and integrate constraint removal efforts (He et al., 2023; He, Liu, Zhang, et al., 2022). Although research on constraint removal is abundant, there has been a lack of research on quantifying the interrelated relationships between different constraints in terms of project schedule and cost. This research will fill this gap.

SMART CONTRACT IN CONSTRUCTION

The term "smart contract" was coined by Szabo (1994). He defined the smart contract as "a computerized transaction protocol that executes the terms of a contract." The smart contract runs on a blockchain and can execute predefined consensus automatically once certain events are detected. All the transaction data will be recorded in a distributed ledger, namely blockchain, to track conditioned events and executions. Smart contracts showed a 200% improvement in information-sharing accuracy compared with traditional digital payment tools (Hamledari & Fischer, 2021a). Smart contracts demonstrated great potential in streamlining the construction business, such as assigning progress payments (Hamledari & Fischer, 2021b), coordinating supply chain orders (Lu et al., 2021), and triggering rework where defects occurred (Wu et al., 2021). The introduction of smart contracts in the construction industry can remedy the deficiencies of centralized control (Yang et al., 2020) and enhance process automation (Mason & Escott, 2018).

Construction projects are characterized by dynamic and uncertain processes that involve tangible and intangible constraints interrelated with each other. Although smart contracts have been widely adopted in the construction industry, they are not inherently "intelligent" enough to handle different uncertainties ex-ante, and their design heavily relies on individuals who construct the underlying consensus. Poorly designed smart contracts may lead to irreversible financial loss (Hamledari & Fischer, 2021a). Hence, ensuring the flexibility of smart contracts in handling unexpected events is critical for their successful implementation in the real world (Hunhevicz et al., 2021). Various research efforts have been made to facilitate the practical adoption of smart contracts by modeling constraints in their design. For instance, Wu et al. (2021) proposed a formal ontology to represent constraints in construction quality regulations, aiming to improve blockchain's interoperability and support the auto-generation of smart contracts by strengthening the reasoning ability of ontology. Another study by X. Li et al. (2022) highlighted the challenges in developing adaptive smart contracts that can provide solutions for constraints, risks, uncertainties, and disturbances. They acknowledged that including them in each transaction leads to redundancy and low latency for the blockchain network. Furthermore, Chen, Liu, Zhang, et al. (2023) conducted a simulation study to elaborate on various levels of prerequisite work readiness as the primary constraint for smart contracts to enforce a reliable critical path workflow. Simulating different "what-if" scenarios and conducting cost-benefit tradeoffs in real-time demonstrated significant implications for robust smart contract consensus design. Dounas & Lombardi (2022); He, Liu, Wang, et al. (2022) emphasized the importance of standardized smart contract design to enhance context awareness. However, the design of smart contracts barely considered the seven types of constraints that are the leading factors of construction "waste." This study aims to investigate the interactive constraint relationships to present a situation-awareness smart contract.

DATA COLLECTION

Data was collected from a high-rise residential building project in Singapore that utilized the modular construction method for Prefabricated Bathroom Unit (PBU) installation. The project aimed to complete 120 PBU installations, with equal distributions of three different types: 40 PBUA, 40 PBUB, and 40 PBUC. The project had three major participants: a PBU fabricator responsible for off-site fabrication and delivery, a crane and operator responsible for platform installation and lifting, and workers responsible for installation. The major constraints included uncertain and out-of-sequence PBU arrival due to the fabricator's preference for producing PBUs in a large batch, crane unavailability due to fully scheduled lifting activities, and a minimal number of workers assigned for installation to maximize profitability. This worsened the vicious cycle of arrival-lifting-installation. Besides, heavy rainfall was frequent in Singapore (Shen et al., 2018), which can significantly hinder installation productivity. Therefore, considering external conditions (e.g., precipitation intensity) as the fourth constraint is also crucial during the project planning stage.

RESEARCH METHODS

Figure Figure 1 presents the research framework, which involves six main steps. First, the study identified four key constraints for the real case project, namely external conditions (EC), material availability (MA), equipment availability (EA), and labor availability (LA). In step 2, the research defined three levels of variability for each constraint and used them to construct a simulation model that generated 81 possible scenarios. The scenarios were evaluated based on cost, and a Shapley value approach was used to determine fair reward/penalty sharing rules. In step 5, the researchers programmed all the scenarios and payment terms into smart contracts to incentivize collaborations and ensure high reliability. Finally, the framework's validity and effectiveness were tested through various scenarios input.

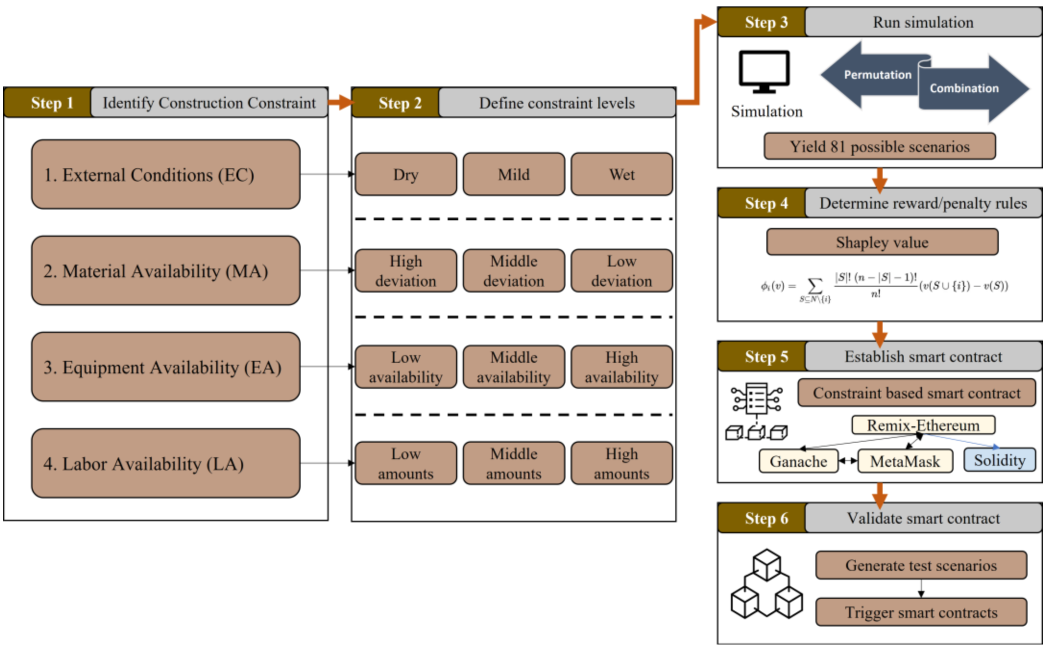

Figure 1: Research framework

Simulation Modeling

The research collected data on 74 PBU loading platform assemblies and 139 PBU hoisting activities. The productivity distribution processing can be referred from previous work (Chen et al., 2022). Productivity distribution is used used to build a simulation model that considers four main constraints: precipitation intensity (EC), PBU delivery reliability (MA), crane availability (EA), and assigned worker amounts (LA). These variables were used to evaluate the impacts on the project's overall outcomes.

The weather in Singapore can be categorized into dry, wet, and mild seasons, as reported by the National Environment Agency (2009). The historical daily precipitation data for 2017 was obtained by web scraping from the Meteorological Service Singapore (2023), which provided 151 daily precipitation intensity records for dry weather and 91 and 123 records for mild and wet weather, respectively. Larsson & Rudberg (2019) identified that different levels of precipitation intensity affect work efficiency, with the efficiency decreasing as precipitation intensity increases. Based on their findings, different weather conditions have varying precipitation intensity probability distributions, which are displayed in Figure 1. The reliability levels for PBU, crane, and workers, as well as the simulation workflow, can be found in our previous work (Chen, Liu, Li, et al., 2023; H. Li et al., 2023), which also outlines the three different levels of reliability for each constraint as summarized in Table 1. These different levels of variability can be combined and permuted to produce 81 possible scenarios.

The simulation recorded the project duration of 120 PBU installations, and the wait time for the crane and installation workers. The project cost includes PBU material costs, crane rental costs, workers' salaries, and indirect costs. Each PBU costs \$5,400 to fabricate, \$648,000 for 120 PBUs in total. Crane costs \$1,200/day, one installation team costs \$1,000/day, and the indirect cost is \$2,000/day. The project outcomes will be quantified in terms of cost to evaluate the marginal contributions from each constraint.

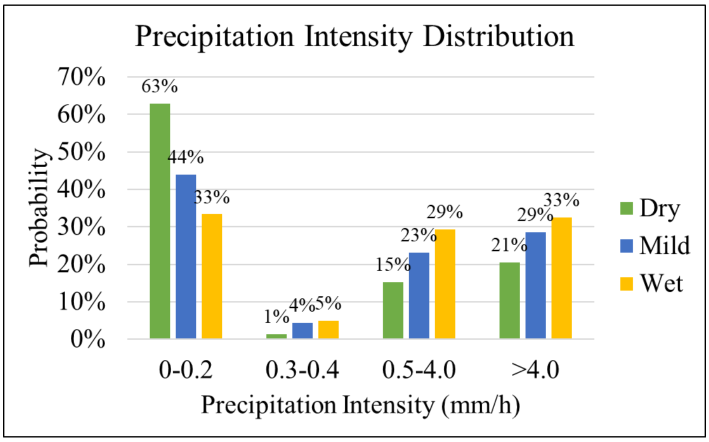

Figure 2: Influence of Precipitation on Construction Efficiency Based on Different Weather Conditions

Table 1: Reliability Level for Four Constraints

Reliability	Measurements	
EC	Precipitation Intensity	Distribution
High	Dry	DISC(0.63, 1, 0.64, 0.6, 0.79, 0.5, 1, 0.3)
Middle	Mild	DISC(0.44, 1, 0.48, 0.6, 0.71, 0.5, 1, 0.3)
Low	Wet	DISC(0.33, 1, 0.38, 0.6, 0.67, 0.5, 1, 0.3)
MA	PBU Delivery Deviation	Distribution
High	(0,8]	DISC(1/3, PBU_x, 1/3, PBU_y, 1, PBU_z)
Middle	(8,14]	DISC(11/18, PBU_x, 15/18, PBU_y, 1, PBU_z)
Low	(14,24]	DISC(15/18, PBU_x, 17/18, PBU_y, 1, PBU_z)
EA	Crane Availability	Distribution
High	>= 80%	80%
Middle	(60%, 80%)	70%
Low	<= 60%	60%
LA	Assigned Worker Amounts	Distribution
High	(7, 10]	U(66, 76)
Middle	(4, 7]	U(80, 90)
Low	<= 4	U(100, 111)

Note: DISC(Cumulative Probability, Value, ...) : discrete probability distribution; U(a, b) : Uniform Distribution

Shapley Value Calculation

The Shapley value method is a way to fairly and efficiently share benefits among a group of players (Parrachino et al., 2006). It assumes that a collaboration of n players can be represented by a set of players N, and a coalition of players S, with $v(S)$ measuring the sum of payoffs from members of S due to cooperation. Each player's contribution to the coalition can be measured using the formula:

$$\varphi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(n-|S|-1)!}{n!}(v(S \cup \{i\}) - v(S)) \quad (1)$$

Where n is the total number of players, $v(S \cup \{i\}) - v(S)$ is the difference of worth when adding player i in coalition S, and $S \subseteq N\{i\}$ is the subsets S of N not containing player i. This formula can be used to calculate the fair reward or penalty for each player.

For example, suppose the objective is to determine the equitable reward for PBU fabricators in a scenario where all players (MA, EA, and LA) take part in a High (H) reliability collaboration, where the benchmark is Middle (M) reliability collaboration. The Shapley value method can be employed in the following manner:

1. Calculate the marginal value of adding each player (MA, EA, and LA) to the coalition, which can be represented as $[\Delta v_{\emptyset,MA}, \Delta v_{EA,MA}, \Delta v_{LA,MA}, \Delta v_{(EA,LA),MA}]$, and their values are [$1,722, $630, $504, $42].
2. Determine the scaling factor for each subset size, which averages the effect of the rest of the team members, ignoring their composition and focusing solely on the player's marginal contribution. The scaling factors for $[\Delta v_{\emptyset,MA}, \Delta v_{EA,MA}, \Delta v_{LA,MA}, \Delta v_{(EA,LA),MA}]$ are [1/3, 1/6, 1/6, 1/3], respectively.
3. Calculate the fair reward for each player by multiplying the scaling factor for each subset size by the marginal value of adding that player to the coalition and summing the results. The fair rewards for players PBU fabricator (responsible for MA) are 1/3 × $1,722 +1/6 × $630+1/6 × $504 +1/3 × $42 = $777.

Therefore, according to the Shapley value method, PBU fabricators, crane, and workers should receive benefits of $777, $861, and $21,672 when all players participate in the High collaboration. Shapley values can be negative if a player's participation causes a decrease in overall project performance, indicating that the player should be penalized for their contribution. For example, once (M, M, M) has been set as benchmark, the penalties for case (L, L, L) can be calculated by forming the following eight combinations: (M, M, M), (L, M, M), (M, L, M), (M, M, L), (L, L, M), (L, M, L), (M, L, L), (L, L, L).

Table 2: Sample of Shapley Value Calculation

Case	(MA, EA, LA)	Duration	Total Cost	Difference	PBU SV	Crane SV	Worker SV
1	(M, M, M)	44.24	$ 833,808	$ -	$ -	$ -	$ -
2	(H, M, M)	43.83	$ 832,086	$ 1,722	$ 1,722	$ -	$ -
3	(M, H, M)	44.01	$ 832,842	$ 966	$ -	$ 966	$ -
4	(M, M, H)	39.04	$ 811,968	$ 21,840	$ -	$ -	$ 21,840
5	(H, H, M)	43.86	$ 832,212	$ 1,596	$ 1,176	$ 420	$ -
6	(H, M, H)	38.92	$ 811,464	$ 22,344	$ 1,113	$ -	$ 21,231
7	(M, H, H)	38.70	$ 810,540	$ 23,268	$ -	$ 1,197	$ 22,071
8	(H, H, H)	38.69	$ 810,498	$ 23,310	$ 777	$ 861	$ 21,672

*SV: Shapley value

SMART CONTRACT DEVELOPMENT

Eighty one possible scenarios formulated "management intelligence" and were translated into smart contract codes in Solidity language (version 0.8.14). This research developed smart contracts in Remix-Ethereum (version 0.29.2), which has an online Integrated Development Environment (IDE) that is a powerful toolset for developing, deploying, debugging, and testing Ethereum and Ethereum Virtual Machine (EVM)-compatible smart contracts. The IDE also has the desktop version for programmers who prefer the performance or security on their own hard drives. Besides, this study utilized Ganache (version 7.2.0) to create a private Ethereum blockchain and created accounts for three parties: PBU fabricator, crane, and installation workers. Ganache enables setting a personal Ethereum blockchain on the local network for testing and development so that the smart contract programmer can simulate different blockchain nodes in one computer before practical implementation. Ganache provides a Remote Procedure Call (RPC) link that allows smart contracts to run on the fetched blockchain network. The Remix-Ethereum can enter the PRC link in the "Environment" tab to deploy developed smart contracts in created blockchain. Once the blockchain is deployed, project participants can use MetaMask 10.11.3 (a decentralized crypto wallet) as a tool to interact with the blockchain and smart contract. Once all the settings have been settled, different scenarios can be generated to test the validity and effectiveness of proposed smart contracts.

RESULTS

The simulation outputs are summarized in Table 3. The results of non-weather consideration were also included in the table. Without weather considerations, the average project duration for 27 scenarios is 32.27 days, and the wait time for the crane and installation worker team are 0.97 hours/PBU, and 0.34 hours/PBU, respectively. While with weather (dry) considerations, the project duration is 46.17 days, showing a 43.08% increase. Figure 2 indicates that even during dry weather, there are precipitation intensities >4.0 and 0.5-4.0 mm/h, which cause a decrease in production efficiency, ultimately resulting in a significant increase in overall durations compared to situations without weather considerations. The crane and installation workers' wait times were 1.81 hours/PBU and 0.21 hours/PBU, respectively. This led to an 87.63% increase in crane wait time and a 37.52% decrease in installation worker team wait time under weather assumptions. The crane had more idle time, while the installation workers were busier. Project duration increased by 14.95% for mild weather (53.07 days) and by 23.62% for wet weather (57.08 days) compared to dry weather. Crane idle time increased by 23.07% (2.23 hours/PBU) for mild weather and by 36.18% (2.47 hours/PBU) for wet weather, while workers' wait time decreased by 18.43% and 26.05%, respectively. These results suggest that severe weather (increased precipitation intensity) can increase project duration and crane idle time, while putting more pressure on installation workers. Weather affects task productivity, and the worker installation capacity cannot match the high PBU delivery and crane capacity during turbulent weather. According to the Goldratt & Cox (1984), a bottoleneck operation is the operation that limits the capacity of the entire production process, and it can be identified by high levels of capacity utilization of the resources. Therefore, the activities of installation workers became the bottlenecks in this production process.

Table 3: Comparisons of 108 Scenarios from Simulation

	Without Weather (Chen et al., 2023)			With Weather (Dry)			With Weather (Mild)			With Weather (Wet)		
(MA, EA, LA)	Duration	Crane WT*	Worker WT	Duration	Crane WT	Worker WT	Duration	Crane WT	Worker WT	Duration	Crane WT	Worker WT
(L,L,L)	38.90	1.01	0.55	53.71	1.97	0.29	61.73	2.47	0.23	66.22	2.77	0.19
(L,L,M)	37.40	0.94	0.80	48.18	1.48	0.46	54.59	1.87	0.38	57.72	2.02	0.29
(L,L,H)	35.70	0.79	0.92	44.76	1.21	0.58	48.86	1.41	0.40	52.41	1.62	0.35
(L,M,L)	37.30	1.40	0.42	53.38	2.46	0.26	61.49	2.94	0.22	65.98	3.23	0.19
(L,M,M)	34.30	1.19	0.56	47.13	1.92	0.35	53.23	2.29	0.27	56.52	2.47	0.21
(L,M,H)	32.70	1.04	0.68	43.05	1.60	0.44	47.66	1.86	0.33	51.27	2.04	0.31
(L,H,L)	37.80	1.88	0.47	52.86	2.79	0.23	60.56	3.29	0.21	65.96	3.64	0.18
(L,H,M)	34.10	1.53	0.53	46.86	2.31	0.34	52.26	2.59	0.20	56.95	2.90	0.23
(L,H,H)	31.60	1.35	0.59	42.53	1.94	0.38	48.11	2.28	0.33	50.28	2.33	0.23
(M,L,L)	34.20	0.64	0.17	51.68	1.79	0.13	61.25	2.45	0.11	64.71	2.60	0.12
(M,L,M)	33.00	0.56	0.44	45.67	1.26	0.24	51.90	1.67	0.17	56.33	1.91	0.17
(M,L,H)	31.60	0.43	0.58	41.36	0.96	0.31	46.76	1.22	0.22	50.10	1.44	0.17
(M,M,L)	33.70	1.13	0.11	51.39	2.32	0.10	59.72	2.80	0.09	64.93	3.19	0.10
(M,M,M)	30.40	0.84	0.21	44.24	1.69	0.13	51.33	2.13	0.11	55.21	2.36	0.10
(M,M,H)	28.30	0.67	0.31	39.04	1.25	0.11	45.01	1.63	0.11	49.06	1.84	0.10
(M,H,L)	33.10	1.48	0.08	51.43	2.66	0.08	60.10	3.24	0.08	64.71	3.54	0.09

(M,H,M)	29.60	1.18	0.15	44.01	2.05	0.08	50.97	2.51	0.08	55.37	2.74	0.09
(M,H,H)	27.20	0.95	0.21	38.70	1.63	0.09	45.30	2.01	0.09	48.78	2.22	0.08
(H,L,L)	33.80	0.64	0.12	52.02	1.85	0.12	60.22	2.35	0.12	64.99	2.70	0.12
(H,L,M)	32.00	0.50	0.36	45.35	1.32	0.20	52.33	1.71	0.17	56.24	1.92	0.15
(H,L,H)	30.20	0.33	0.47	41.22	0.92	0.30	46.51	1.23	0.21	49.92	1.37	0.18
(H,M,L)	33.00	1.06	0.05	51.64	2.31	0.09	60.04	2.85	0.09	64.82	3.18	0.10
(H,M,M)	28.80	0.74	0.09	43.83	1.67	0.09	51.38	2.11	0.10	55.22	2.34	0.10
(H,M,H)	26.70	0.52	0.16	38.92	1.26	0.11	45.52	1.65	0.11	48.79	1.86	0.10
(H,H,L)	32.40	1.42	0.02	51.14	2.67	0.07	60.08	3.25	0.08	64.88	3.56	0.09
(H,H,M)	28.30	1.07	0.04	43.86	2.06	0.07	51.08	2.50	0.08	54.95	2.73	0.09
(H,H,H)	25.20	0.82	0.05	38.69	1.64	0.08	45.03	1.97	0.08	48.81	2.20	0.09
Average	32.27	0.97	0.34	46.17	1.81	0.21	53.07	2.23	0.17	57.08	2.47	0.16

*WT: Wait Time (Hours/PBU)

Table 4 presents the rewards and penalties under 81 scenarios for PBU fabricators, crane operators, and installation workers responsible for MA, EA, and LA under different weather conditions. Each value is aggregated using generated cost from simulation and Shapley value calculation described previously. The value corresponds to the marginal contributions of this responsible specialty under that scenario. Figure 3 visualizes the Shapley values based on the marginal contributions from each participant, with the height of each bar column indicating the Shapley value payments or contributions of each participant. Figure 3 (a) showed that without considering the impact of weather, PBU delivery excelled over than other two factors in contributing to successful project outcomes. With weather considerations and as weather conditions got worse, the installation workers dominated the project contributions. During wet weather, the contributions from higher reliability of crane and PBU delivery are minimum. It is essential to prioritize installation worker assignments either by assigning an extra installation team or extending the working time to overcome extreme external conditions. These 81 payment rules will be encoded into smart contracts as an incentive mechanism to enable reliable constraint removal for decentralized production planning.

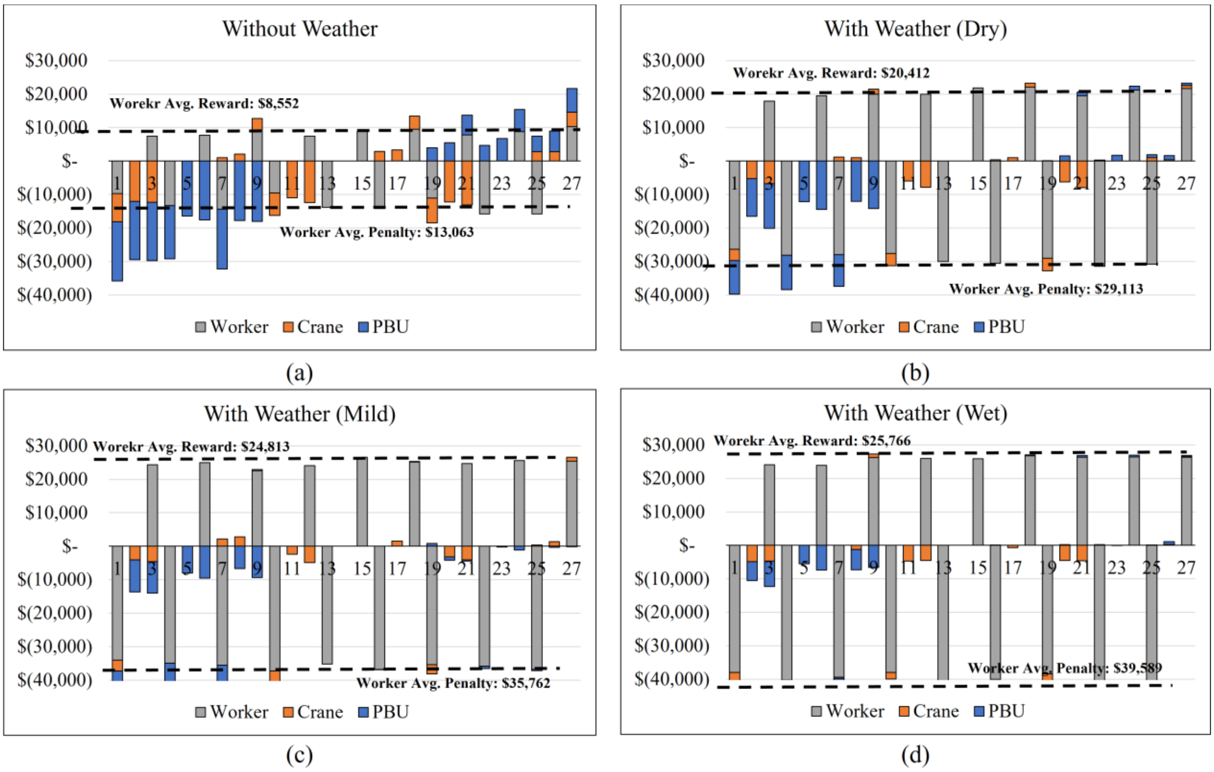

Figure 3: Shapley Value Payments Under Different Weather Scenarios: (a) Without Weather; (b) With Weather (Dry); (c) With Weather (Mild); (d) With Weather (Wet)

Table 4: Payments Based on Shapley Value for 108 Scenarios

	With Weather (Dry)			With Weather (Mild)			With Weather (Wet)		
(MA, EA, LA)	PBU SV	Crane SV	Worker SV	PBU SV	Crane SV	Worker SV	PBU SV	Crane SV	Worker SV
(L,L,L)	-$10,038	-$3,402	-$26,334	-$6,454	-$3,157	-$34,069	-$5,656	-$2,590	-$37,996
(L,L,M)	-$11,340	-$5,208	$0	-$9,639	-$4,053	$0	-$5,670	-$4,872	$0
(L,L,H)	-$13,370	-$6,755	$17,941	-$9,338	-$4,655	$24,367	-$7,588	-$4,732	$24,080
(L,M,L)	-$10,248	$0	-$28,140	-$7,707	$0	-$34,965	-$4,956	$0	-$40,278
(L,M,M)	-$12,138	$0	$0	-$7,980	$0	$0	-$5,502	$0	$0
(L,M,H)	-$14,490	$0	$19,488	-$9,555	$0	$24,969	-$7,392	$0	$23,940
(L,H,L)	-$9,436	$1,211	-$27,979	-$5,446	$2,219	-$35,539	-$5,425	-$343	-$39,382
(L,H,M)	-$12,054	$1,050	$0	-$6,699	$2,793	$0	-$6,069	-$1,239	$0
(L,H,H)	-$14,210	$1,477	$19,975	-$9,352	$350	$22,526	-$6,587	$1,057	$26,236
(M,L,L)	$0	-$3,612	-$27,636	$0	-$4,410	-$37,254	$0	-$1,890	-$38,010
(M,L,M)	$0	-$6,006	$0	$0	-$2,394	$0	$0	-$4,704	$0
(M,L,H)	$0	-$7,875	$19,971	$0	-$4,872	$24,066	$0	-$4,536	$25,998
(M,M,L)	$0	$0	-$30,030	$0	$0	-$35,238	$0	$0	-$40,824
(M,M,M)	$0	$0	$0	$0	$0	$0	$0	$0	$0
(M,M,H)	$0	$0	$21,840	$0	$0	$26,544	$0	$0	$25,830
(M,H,L)	$0	$399	-$30,597	$0	-$42	-$36,792	$0	$126	-$40,026
(M,H,M)	$0	$966	$0	$0	$1,512	$0	$0	-$672	$0
(M,H,H)	$0	$1,197	$22,071	$0	$147	$25,179	$0	$252	$26,754
(H,L,L)	$147	-$3,801	-$29,022	$847	-$2,786	-$35,399	-$266	-$2,366	-$38,444
(H,L,M)	$1,533	-$6,195	$0	-$1,008	-$3,192	$0	$168	-$4,494	$0
(H,L,H)	$1,078	-$7,910	$19,516	-$378	-$4,074	$24,696	$490	-$4,592	$26,320
(H,M,L)	$336	$0	-$31,416	-$777	$0	-$35,805	$210	$0	-$40,572
(H,M,M)	$1,722	$0	$0	-$210	$0	$0	-$42	$0	$0
(H,M,H)	$1,113	$0	$21,231	-$1,176	$0	$25,578	$546	$0	$26,418
(H,H,L)	$910	$973	-$30,863	-$343	$392	-$36,799	$119	$35	-$40,768
(H,H,M)	$1,176	$420	$0	-$336	$1,386	$0	$861	$231	$0
(H,H,H)	$777	$861	$21,672	-$126	$1,197	$25,389	$427	$123	$26,320

*SV: Shapley Value

VALIDATIONS

Test scenarios are generated to validate the smart contract executions, as shown in Figure 4. In this study, smart contracts can only be triggered by a mutual-agreed database. The database can be integrated with various platforms, representing the physical state of the current construction performance. To facilitate data input, this study encoded “2”, “1”, and “0” as the high, middle, and low reliability level, respectively. The environment was be set up as Ganache Provider with four initiated accounts. The first step involved inputting participants’ information and corresponding constraint levels. Given a scenario in that wet weather, high reliability for PBU delivery, crane, and worker involvement was detected from the database, the decoded labels were “0”, “2”, “2”, and “2,” correspondingly. According to the simulation results, the PBU fabricator, crane, and installation workers should receive 427, 123, and 26,320 ether (1 ether = $1 in this study), respectively. In step 2, once the smart contract was successfully activated, the “SendNotice” function would broadcast to the blockchain network regarding the payment amounts for each participant. Step 3 showed that smart contracts could successfully recognize the situations and will assign the correct amounts of payments under this scenario. Solidity provides *transfer()* function that can easily transfer the ether to targeted accounts. Once the transactions were performed, all the information was updated and stored in the blockchain simultaneously, where project participants could view the transactions through Ganache or their digital wallet. The results demonstrated the validity of the developed smart contracts.

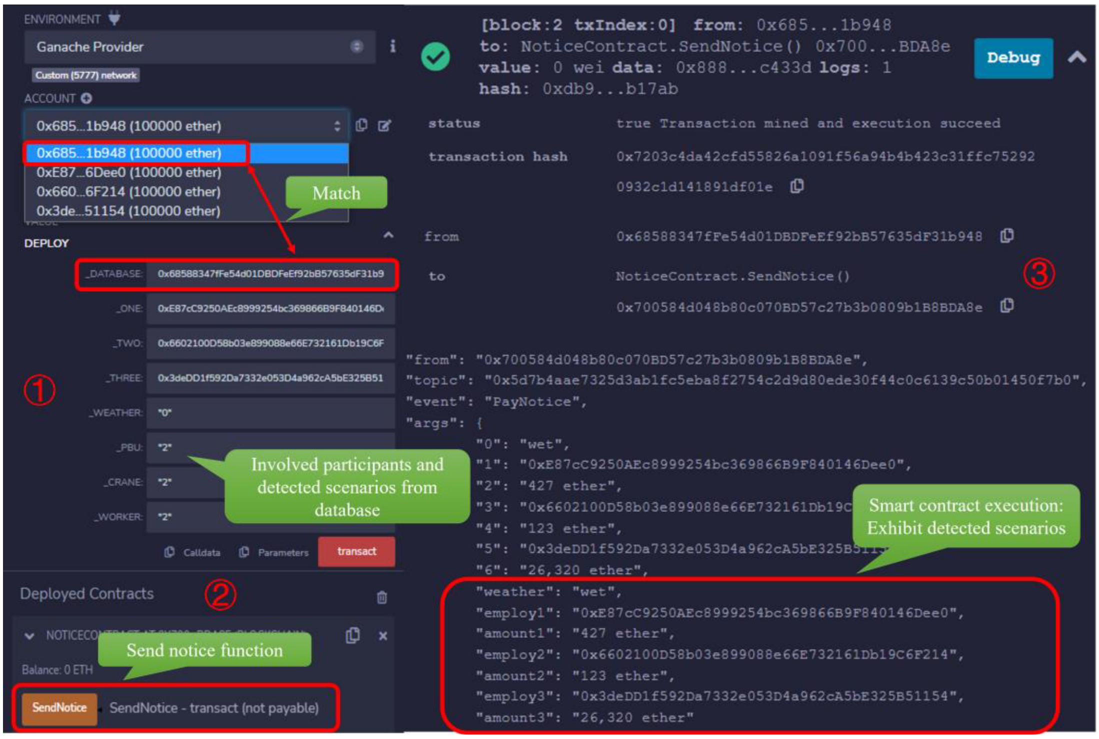

Figure 4: Smart Contract Executions in Remix-Ethereum

CONCLUSIONS

Smart contracts hold immense potential in streamlining the construction process by specifying detailed task planning and enforcing consensus executions. Nonetheless, the dynamic and uncertain nature of construction projects, coupled with tangible or intangible constraints, poses challenges to the effectiveness of smart contracts in dealing with uncertainties ex-ante, relying heavily on individuals who design the underlying consensus. To enhance situation awareness in a decentralized constraint removal system, this study modeled the interactions of constraints in the smart contract consensus, developing a simulation model by permutating four constraint levels to generate 81 scenarios. An equitable payment method based on the Shapley value algorithm was established to incentivize reliable constraint removal. The findings revealed that installation workers dominated project contributions during adverse weather conditions, as installation speed is slower than PBU delivery and crane activities. Consequently, the installation capacity fails to keep up with the delivery and lifting capacity, thereby underscoring the importance of ensuring sufficient installation workers/teams on-site to guarantee project success during extreme weather conditions. Notably, the smart contract executions attested to the accuracy and validity of the developed framework.

This research makes two contributions. Firstly, it quantified the dominant constraints in the face of interactive uncertainties. The flow of constraints is challenging to model and quantify in terms of project outcomes. However, the simulation, which integrated the Shapley value algorithm, exhaustively evaluated all possible scenarios and identified the marginal contributions of improving each constraint. Consequently, project managers can determine the most effective sequence to remove constraints. Secondly, the study integrated blockchain and lean constraint removal theory to enhance smart contracts' situation awareness in dynamic construction environments. Decentralizing construction management requires smart contracts to be "intelligent" enough to function similarly to centralized project managers. The developed smart contract anticipated the governed constraints before the tasks were released into production. Thus, the smart contract focuses on the make-ready process, proactively avoiding situations where crews wait for conditions to mature instead of reactively resolving them with centralized control intervention.

LIMITATIONS

This study has several limitations. First, due to the limitations of the available data, this research only considered the four major constraints that impacted the projects in smart contracts, whereas Koskela (1999) suggested that at least seven types of constraints should be removed during construction planning. Future research can investigate modeling seven constraints and their interactive relationships in smart contracts. Second, this study assumed the extracted information from a database could be used to activate smart contract executions. However, it is difficult to establish a comprehensive database as well as construct contextualization that guarantees reliable smart contract execution. The deployment in the test environment represents another limitation.

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CASE STUDY – LEAN PROJECT MANAGEMENT IN A MULTI-PROJECT ENVIRONMENT

Maximilian R.-D. Budau[1] and Tobias Juchum[2]

ABSTRACT

Lean project management approaches such as the Last Planner System (LPS) have already been proven their worth in numerous case studies. Lean project management generally contributes to the optimization of schedule execution and the project-related resource utilization. However, this often ignores the fact that a company usually strives to optimize its use of resources at the corporate level. Therefore, a specific approach was developed and tested in a case study in cooperation with a medium-sized company. This study utilizes the Design Science Research (DSR) approach, drawing on existing approaches to problem solving. The developed Multi-Project LPS (MPLPS) approach shows significant potential for cross-company resource optimization after only a few weeks of application.

KEYWORDS

Last Planner® System, collaboration, pull planning.

INTRODUCTION

A major challenge for construction companies is to optimize the allocation of resources across projects. Large construction companies frequently use software to support this process. Medium-sized companies often have to find another way for cost reasons. In the company considered in this case study, one employee is responsible for resource allocation. This person must try to find an optimum in exchange with the individual construction sites. By optimizing the use of resources in the form of machines, materials and personnel on one construction site at the expense of another, this can lead to a situation where, at the end of a fiscal year, the company's results do not correspond to what would have been possible in the best case. The company in question recognized this problem and attempted to find a solution that would at least identify bottlenecks in resource planning at an early stage. Such an approach would be a first step towards the cross-project optimization of resource utilization within a company. To develop this in the present case study, the so-called Design Science Research (DSR) approach is used. The basic procedure is shown in Figure 1.

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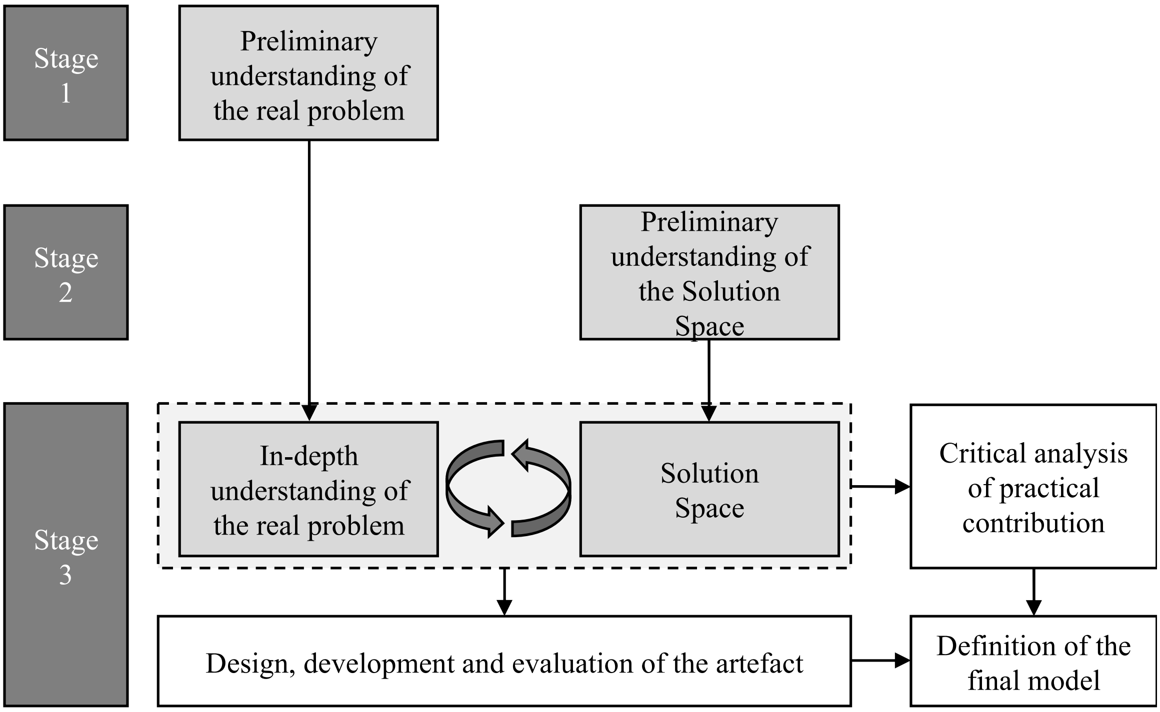

Figure 1: A visualization of the method and structure of this paper (Dresch et al. 2015; Hamerski et al. 2019).

As the figure shows, the first step in DSR is to identify the problem and break it down into its core components. To do this, this case study examined individual projects of the construction company as well as the distribution of resources within the company.

A literature search was conducted in the second step to form the so-called solution space. In particular, the IGLC served as a platform for the research. The approaches identified in this way formed the solution space alongside fundamental approaches to lean construction, such as the LPS.

In the third step, the extent to which the solution space provides solutions for the problem under consideration was tested in an iterative process. The aforementioned medium-sized company, which agreed to participate in the cross-company test, served as the data supplier. Within the framework of individual projects, it was possible to test the benefits of individual approaches from the solution space before these could gradually be put together to form a holistic solution approach. This process results in a multi-project management approach according to lean principles.

This study summarizes the development process results and presents the results of the first applications, the so-called Multi-Project Last Planner System (MPLPS). Finally, the results are summarized, and possible limitations of the investigation are pointed out.

STAGE 1: PROBLEM SPACE

PROJECT OVERVIEW

The research began in early 2022. The construction company considered here had 10 ongoing projects at that time. Table 1 provides an overview of these projects. The projects were mainly high-rise construction projects and a large part of them were in the remodeling sector. The company provided access to all of the projects as well as access to all of the documentation. Access consisted of the authors being able to attend all resource planning meetings and were given access to all data associated with this.

Table 1: project overview

Project	Project size (Million €)	Project art
1	3	new building
2	5	rebuilding
3	3	rebuilding
4	1	rebuilding
5	11	new building
6	5	new building
7	8	new building
8	1	rebuilding
9	2	rebuilding
10	4	rebuilding

IDENTIFIED PROBLEMS

The first weeks of the development process were used to analyze the main problems and to understand the problems identified, as provided for in the DSR. In many cases, problems cannot be reduced to a single cause. It was therefore necessary to focus on individual aspects. The results of this analysis process are the following problems, which need to be solved, as far as possible with the help of the model developed here:

- Problem 1: Resource bottlenecks are often not recognized until they have already occurred.
- Problem 2: Resource allocation requires a lot of coordination work by the resource manager.

In the following, the so-called solution space will be discussed first. This is the result of a literature research on similar and related problems. In the following step, an artifact is proposed based on the presented solution space, which solves the problems presented here, if possible.

STAGE 2: SOLUTION SPACE

PROJECT-SPECIFIC RESOURCE OPTIMIZATION: LAST PLANNER SYSTEM

The Last Planner® System (LPS) is a method for increasing productivity and stabilizing workflows. It was developed by Glenn Ballard and Gregory Howell and involves all project stakeholders in schedule and subcontractor control. The idea of LPS is to take a backward look at scheduling. (Ballard 2000)

First, the entire project is considered and milestones are defined for individual process phases. In a second step, a week-by-week phase schedule is used to define tasks to maintain the flow of work in the coming weeks. (Fiedler 2018) Last Planner meetings are used to check the targets set in the work plans, identify any errors and their causes, record the reason, and include the consequences in schedules and milestone plans. The interval of the meeting depends on the size of the project (e.g., weekly). When errors occur, such as incomplete or faulty work, the affected project participant can stop production. "This person is referred to as the Last Planner." (Heidemann 2011)

CROSS-PROJECT OPTIMIZATION

There are numerous lean approaches for optimizing individual construction sites, such as the LPS. The application of these approaches has already been tested and their efficiency has been proven. For the holistic optimization of an organization, there have been initial publications including case studies in recent years. In this context, the three-level approach by Dlouhy et al. (2018), which will be discussed in more detail here, and the multi-project lean management approaches by Bellaver et al. (2022) and Hamerski et al. (2019) are particularly worth mentioning.

Figure 2 shows the 3-level model of customer-oriented construction production according to Dlouhy et al. (2018). According to the authors, the model provides a transparent regulatory framework for structuring construction processes. It organizes an organization's resource and work planning processes into three hierarchical levels, with the level of detail increasing from top to bottom. The processes are closely linked. The following work steps must take place at the three levels:

Macro level: The macro level of the 3-level model represents the basis for communication with the client. The level of detail is reduced to a level that it is sufficient for strategic decisions relating to the entire construction process. The information for this level in turn comes from the levels below it.

Standard level: The standard level has a medium level of detail. It is used to map the construction coordination processes. The macro level provides information and specifications that are adapted to the project at this level. Construction processes are in turn planned and coordinated at this level. Individual processes and their interfaces are optimized. In this way, a stable execution flow can be ensured.

Micro level: The micro level represents the lowest and most detailed level of the 3-level model. Its purpose is to represent the processes that actually take place at the value creation level and to help control and monitor the work performed on a short-cycle basis. It receives instructions from the standard level and, conversely, passes on data and information to the two upper levels.

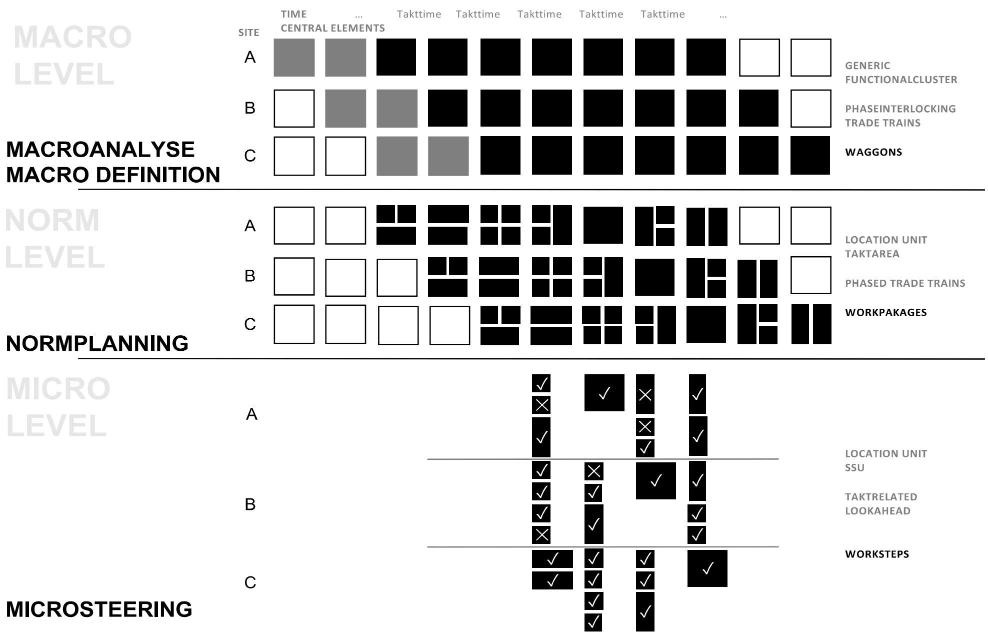

Figure 2: The three-level model (Dlouhy et al. 2018).

These approaches to the cross-project level first show at the principle level how such optimisation could take place. What is missing, however, is a concrete solution or implementation approach, which is the focus here.

INTEGRATED PRODUCTION SYSTEMS (IPS)

The implementation of lean construction often leads to problems in companies. Through various reorganization projects, companies are to be adapted to the Japanese model, and expectations are very high. In many cases, these innovations do not produce any real improvement, which ultimately leads to demotivation of the entire workforce. (Lay et al. 2005)

However, the fault lies not in the nature of the projects or their tools, but in the way they are implemented. Two fundamental problems can be identified that are responsible for the false start of Lean Systems. The first is the lack of stabilization of the new projects. If they do not bring success, they are immediately replaced by other projects. The second mistake is the lack of coordination between different approaches. For example, new types of production systems can strongly influence existing systems. The individual projects within the TPS concept must also be coordinated so that they do not work at cross-purposes. (Lay et al. 2005)

IPS are therefore introduced at the point of implementation. Its goal is to bring together all the concepts of the company in a meaningful way and to eliminate conflicting goals. An IPS is thus not a stand-alone tool. Rather, it is a regulatory instrument for coordinating the introduction of an existing production system. On the one hand, it creates transparency; on the other hand, it combines the strengths of all structures in order to improve the economic efficiency of the company. (Lay et al. 2005)

Every company has a different history and combines different concepts and structures. Therefore, an IPS does not offer a one-size-fits-all solution. Instead, it responds individually to the existing systems, technologies and the associated corporate culture. (Lay et al. 2005)

The IPS is therefore not limited to manufacturing. It tries to extend the new ideas to all relevant areas. (Lay et al. 2005) This applies in particular to upstream and downstream areas such as planning, control and logistics. So, it covers the entire manufacturing process. (Spath 2003)

In addition, IPS has a modular structure. It can be clearly seen what the task of an element is and how it relates to the overall system. This creates transparency and facilitates the operation of the elements. (Lay et al. 2005) To reinforce this effect, it is necessary to define the business objectives. In this way, the modules can be built up more purposefully and, if necessary, linked together. (Spath 2003)

The components of an IPS can be divided into methods and tools. The methods form the basis of the system. They are working techniques, which consist of planned and comprehensible working steps. They specify how a specific tool must be used to reach the desired goal. (Gorecki et al. 2014)

Since a IPS is modular, it can consist of different methods and tools. If a company chooses the components that make the most sense for itself and assembles them into an individual IPS. Since there are many different methods and tools, only the most important ones will be described in the following chapters.

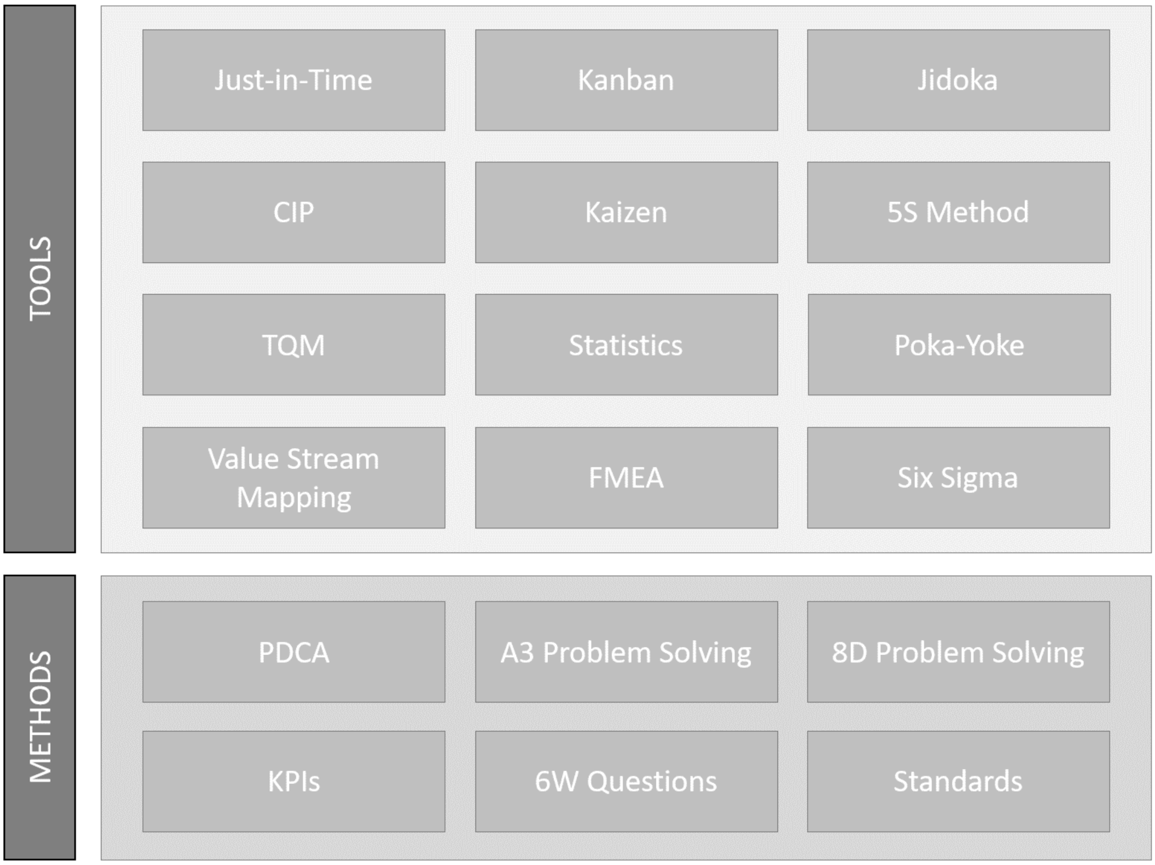

Figure 3: Tools and methods of IPS (Gorecki et al. 2014).

STAGE 3: ARTEFACT

RESULT OF DESIGN AND DEVELOPMENT OF THE ARTEFACT

Initial implementation

A fundamental distinction must be made between the initial setup and the short-cycle adjustments to the planning as the project progresses. In the following, the initial process of setting up the planning of a project will be discussed first. The basic idea of the 3-level model is that it can be used to control a large number of individual projects. In order to take advantage of the strengths of the approach, the following process must be implemented for all construction measures of the company in question.

The initial setup of resource planning for an individual measure is essentially based on the 5-step approach of the Last Planner system in the approach examined here. A special feature here is that the individual planning levels of the LPS are integrated into the levels of the 3-level model by Dlouhy et al. (2018).

According to the LPS, the first step is to perform an overall process analysis for the specific project. Framework data such as completion dates, lock-in periods, etc. are determined, and necessary work steps as well as initial dependencies are identified. The goal of this step is a master plan (milestone plan) with project-specific phase and area classification as well as process steps for each area and possible trade.

In the next step of phase planning, a schedule is created based on the master plan (milestone plan) using common scheduling software such as MS Project. A prerequisite for the functioning of the model presented here is that the software used allows the linking of several phase plans and the allocation of resources. Scheduling should be done on a weekly basis and not more precise.

This phase planning in turn forms the basis for the make-ready planning (6-week preview planning) in the next step. If possible, this should be done at the construction site by the respective trade managers. The 6-week preview can in turn be further specified at the start of the project in the form of weekly work planning (2-week detailed planning).

The make-ready planning (6-week preview planning) and the weekly work planning (2-week detailed planning) are to be integrated at the micro level of the 3-level model, since the optimization of the use of resources takes place here at the project level. At the standard level, the phase planning of the company's individual projects is combined again. By allocating resources, resource conflicts can be identified at this level and adjustments can be passed on to the micro level. Similarly, resource planning at the micro level allows for the automatic derivation of metrics that can be used at the norm level. The same is true for metrics that can be derived from master resource planning at the norm level to support strategic decisions at the macro level. The system used here does not provide for any further information at the macro level beyond key figures such as adherence to schedules.

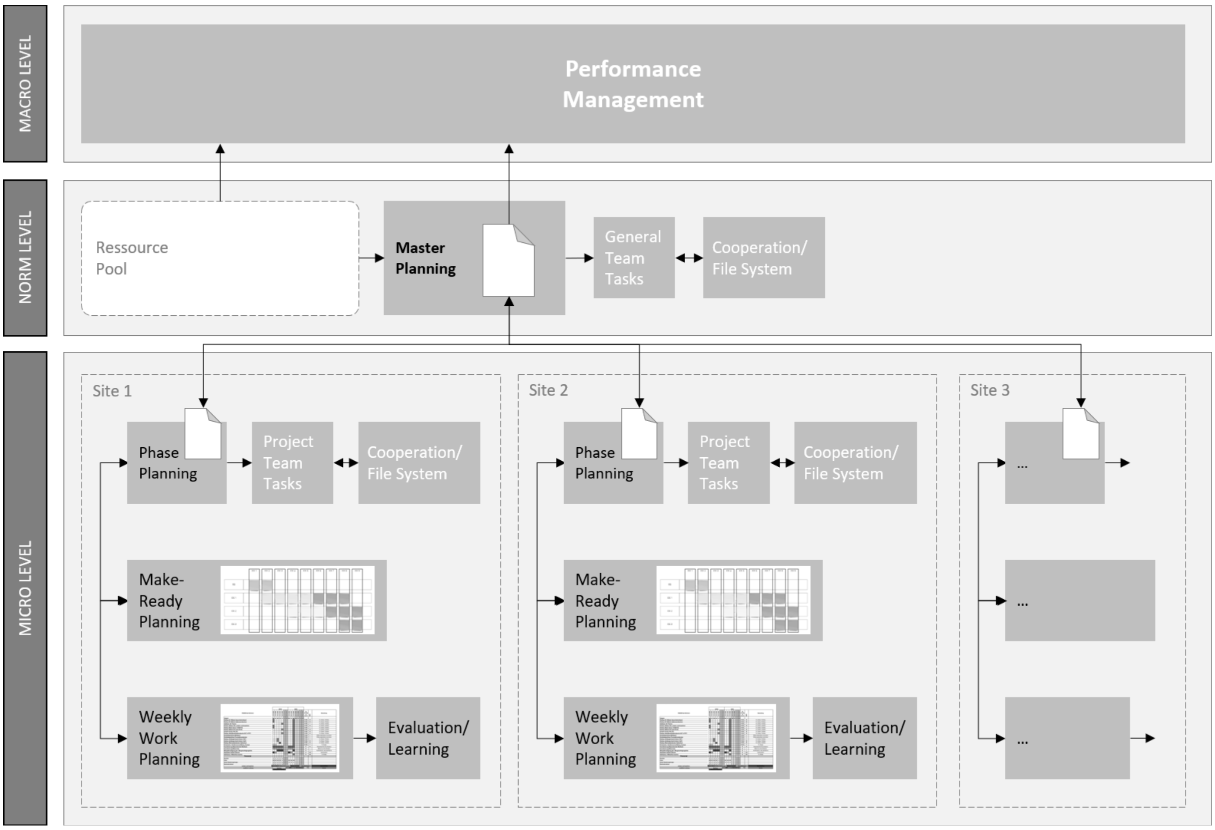

Figure 4: Initial implementation.

Adaptation process

The MPLPS provides that, where possible, a new week is added to the make-ready planning (6-week forecast schedule) and the detailed weekly work planning schedule, or the existing schedules are adjusted. This adjustment process continues to occur as part of the approach presented here. As presented above, this is part of the micro level. The specifics of the process presented here relate in particular to feedback to the norm and macro levels. The basic adaptation process is shown in Figure 4.

After the adjustment of the make-ready planning (6-week forecast plan) and the detailed weekly work planning according to the MPLPS takes place in the first step, the resource master planning on the norm level must take place in the second step. The adjustment of the resource planning must be carried out by the respective site manager. In order to keep the workload as low as possible, the level of detail of the resource master plan at the standard level has been limited to an accuracy of one week. Changes in the phase planning that occur at the micro level should also be identified in order to further reduce the workload. Once the resource master planning is synchronized with the already existing enterprise resource plan, information about resource conflicts is obtained. If this occurs, this information needs to be passed down to the micro level to make appropriate adjustments.

Adjustments to the macro level are automatic. The macro level can use the current metrics to make strategic decisions. The actions that result from these decisions are not standard processes and therefore are not directly addressed in the adjustment process.

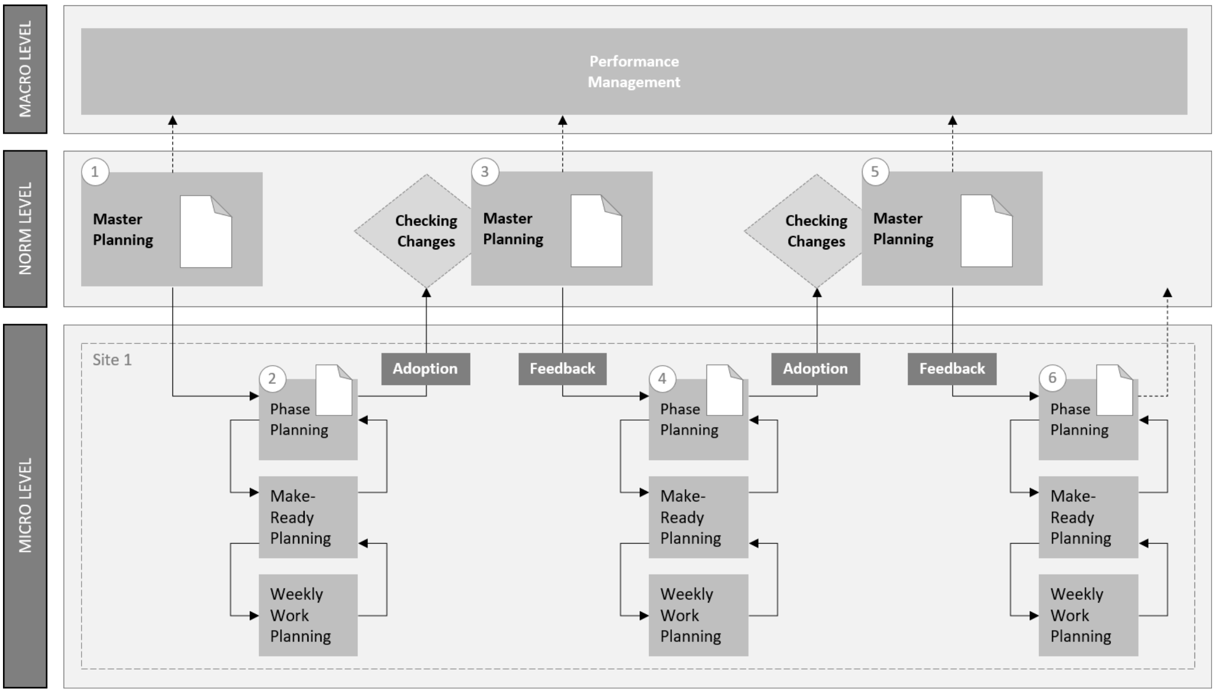

Figure 5: Adoption process.

PRELIMINARY EVALUATION OF THE ARTEFACT

The artefact is still being optimized. A final model could not yet be created. Nevertheless, the artefacts and the current state of the artefact presented here have been repeatedly evaluated in the course of the DSR with respect to solving the problems of the problem space. This can be summarized as follows:

- Problem 1: The developed artefact can effectively identify resource bottlenecks with sufficient lead time.
- Problem 2: Resource allocation is structured by using this artefact. This does not reduce the effort but transforms it into an orderly process.

Only gaps regarding the resources that are the subject of the resource pool can be identified. A resource pool that is too large may lead to too much administrative work. Therefore, the user must weigh up how much administrative effort is reasonable.

The benefit with regard to problem 2 cannot be quantified directly. A structured process does not directly lead to more effectiveness. However, it is the first step on the way to process optimization.

LESSONS LEARNED

The main innovation of the approach considered here is the linked application of LPS on several projects. It is therefore not necessary to report on the experience gained in applying LPS, but to focus in particular on the experience gained at the norm-level. The points that are of importance for the application beyond this are discussed below in bullet points:

- Currently, there is no software solution available that automates the interfaces. The current software solutions that can be used to manage resources do not allow pull planning. As a result, the interfaces must be transferred manually.
- In order to reduce the need to adjust the standard level resource planning when micro-level changes occur, the accuracy of standard-level planning has been reduced to one week.
- One person in the organization is required to take primary responsibility for managing and verifying compliance. The approach developed here helps to find a solution for resource allocation that does not have resource bottlenecks. What it does not do is find the optimal resource allocation solution. This still requires the expertise of the users.

The next step could therefore be to formalize this process further. The individual work packages could then be combined into an optimum overall process with the aid of a production planning system such as is used in stationary industry.

CONCLUSIONS

Optimizing resource utilization across multiple sites is a problem that is too rarely addressed. Approaches such as LPS often only aim to optimize the use of resources on one construction site. Alternative approaches such as the 3-level model help with cross-company optimization. In order to test this, a proprietary approach combining both methods was developed and tested in a medium-sized company. The approach showed great benefit in the context of the company, although its use is associated with considerable effort due to the numerous interfaces that have to be maintained. Therefore, an attempt should be made to find a software solution that digitizes the model.

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DAILY HUDDLES' EFFECT ON CREW PRODUCTIVITY

Søren Wandahl[1], Cristina T. Pérez[2], Stephanie Salling[3], Cecilie H. Hansen[4], Magnus K. Nielse[5], and Tom Nissen[6]

ABSTRACT

Construction labor productivity has always been a key focus point in construction management, particularly for the operational part of the management, i.e., the site managers. Nonetheless, it seems that research on the site managers' tasks and time use is sparse. In the large lean toolbox, several approaches to improving labor productivity and management efficiency are present. One is the Daily Huddle. The objective of this research is to investigate the relationship between Daily Huddles and crew productivity. The research design is case-based, as two cases are analysed, one without and one with Daily Huddles implemented. Data based on Work Sampling of both crew and site manager are collected and analysed. The results show a remarkable distinction in the two cases in both site manager time use and crew productivity. However, a scientifically valid conclusion cannot be reached based on two cases only, thus limitations in the current research design and suggestion for future research are discussed as a contribution to the lean construction society. The practical implication of this study is that the benefit of Daily Huddles has been showcased.

KEYWORDS

Daily huddle, Flow, Productivity, Work Sampling

INTRODUCTION

The interest in understanding labor productivity on the national, project, and individual levels in construction has existed for decades (Abdel-Wahab & Vogl, 2011; Neve et al., 2020a). However, measuring productivity requires data from both earned value (output) and the value of resource use (input), which makes it highly resource-demanding to collect productivity data. Therefore, researchers are searching for other variables that can be used as predictor variables for construction labor productivity. One of these is Direct Work (DW), which is the share of work time that is used for value-adding activities (Handa & Abdalla, 1989; Wandahl et al., 2021). Neve et al. (2020b) investigated this relationship on a project level and found in detail the relationship between value-adding and non-value-adding activities and how these impact productivity through the lenses of transformation-flow-value (Koskela, 2000).

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The Work Sampling (WS) technique has been used for decades to collect data on the amount of value-adding work time, referred to as DW (Gong et al., 2011; Salling et al., 2022). WS is a quantitative approach where data is obtained through direct observations of how workers use their time on the construction site. In general, WS has been applied to improve, often single construction projects regarding efficiency, construction labor productivity, and construction cost and time. In this research, WS is used as an indicator for efficient production.

Lean construction promotes a mindset and provides an extensive toolbox that can be adopted in the management, planning, and production control of construction projects to improve efficiency. One tool is Daily Huddles (DH). A DH is when a team meets before production begins to follow up on yesterday's production and talk about the production of the day. This is typically done in the morning, either in the work zone or at the site office. The purpose of the huddle is to improve alignment and solve problems efficiently, thus making sure that the crew can produce efficiently during the day and particularly improve the startup of the production. In industrial production and manufacturing, short DH plays an important role in day-to-day management and is widely adopted.

Neve et al. (2020b) demonstrated five system behaviors for "low performing" construction production systems, where one was a low share of DW around the start and stop of production, particularly at the start of the workday and at the end of the workday. A vast amount of research has identified and ranked factors influencing construction productivity in general, e.g. (Hamza et al., 2022; Hasan et al., 2018; Naoum, 2016). The results often mention planning systems, communication systems, leadership style, and team integration as high-ranked enablers/disablers for productivity. This is aligned with the purpose of the DH. When reviewing the literature on productivity enablers, it shows that the role of the site manager is under-researched. Site managers are responsible for the operational planning and running of construction activities and have a large interface and communication with the crew. The tasks of the site manager can have a significant impact on crew productivity (Binninger et al., 2018). Therefore, it is relevant to investigate how the site manager spends their working hours at the start of the production and to investigate a potential relationship with construction productivity.

RESEARCH OBJECTIVE

The objective of this research is to investigate the relationship between the site manager's time use and crew productivity in the first two hours of the day. The investigation is based on two case studies, one where DH was implemented and one without DH.

Before explaining the data collection and data analytic methods, a short theoretical introduction to the site manager and DH are presented.

SITE MANAGERS

In the construction industry, site managers are responsible for the day-to-day on site running of a construction project. Site managers are also referred to as construction managers, contract managers, or building managers. They are often responsible for a sub-part of the construction tasks, often divided by trade, i.e., carpenter, foundation, mason, etc. Site managers are required to keep within the time and budget and are involved in both quality control, health and safety checks, and inspection of work carried out. Thus, site managers have a large interface and communication with crew, and the way the site manager plans, manages, and supports the construction project can have a huge influence on crew productivity (Binninger et al., 2018; Fraser, 2000; Koskenvesa & Sahlstedt, 2012). Neve et al. (2020b) argue that the site manager often has a position and holds the insight necessary to be able to overcome daily problems and positively affect both crew and project productivity.

Research addressing site managers in the construction industry is one of the most marginalised fields of interest in construction management studies (Styhre & Josephson, 2006), and most literature has a negative slant. Site managers are depicted as a professional group exposed to conflicting demands and objectives, operating in a complicated environment. For instance, Djebarni (1996) writes: "*Site managers carry out one of the toughest and hardest jobs in the construction process. Site management is characterised by a high work overload, long working hours, and many conflicting parties to deal with, including the management, the subcontractors, the subordinates, the client, etc. This trait of the job makes it very prone to stress*" (Djerbarni, 1996, p. 281).

As described, site managers' tasks are very versatile, as they include dealing with problems arising daily, planning ahead, and accounting for changes that have happened. Thus, some tasks are focused on past production (e.g., claim management, accounting), others are future oriented (e.g., planning, purchasing), and some tasks are focused on present time (e.g., logistics, information, unforeseen events). There is a trend that more and more of the site manager's time is spent on administrative tasks, and less time is spent on facilitating the crew on site. Johansen et al. (2021) report on the site manager's role and defines the concept of visible site management as when the site manager spends time on site assisting the crew with, e.g., answering questions, clarifying production, coordination with other crews, etc. In other words, visible site management is when the site manager focuses on the present time, i.e., the production of the current day, instead of past or future production.

In addition, Johansen et al. (2021) concluded that, especially during the morning start-up, it had a large effect on crew productivity when site managers were visible on the site. Neve et al. (2020b) and Neve et al. (2021) confirm that construction labor productivity is particularly low in the morning and after breaks. Therefore, if the site manager can better facilitate production in the time around production start, it is likely that this could improve productivity. This points towards the implementation of DH, where the site manager assembles his crew every morning.

DAILY HUDDLES

The definition of huddle is to gather or pile together, in this context meaning that people, often in a crew, meet in an informal way. Huddles are also recognized in sports, e.g., during time outs, before starting a play, etc. Daily refers to the frequency, i.e., on a daily basis. It is common to experience different frequencies, like weekly huddles or huddles every two weeks.

The Lean Construction Institute (LCI, 2022) defines a Daily Huddle as "*A daily huddle is a daily check-in for members of a team. It is a method to communicate and measure progress of a team's work plan. Daily huddles allow members to tackle problems prior to missing goals. They also allow the team to review accomplishments from the previous day and to set expectations for the coming day.*" Sometimes, the daily huddle is named differently, e.g., as morning huddle, stand-up meeting, foreman meeting, or even weekly work plan meeting. The important part is not the time of the day, or whether participants are standing or sitting, rather, it is the focus of the activity. In a DH, the focus is on alignment, proactive planning of the day's production, and agility in solving short-term problems fast. The DH meetings are reported to have a short duration of 5 to 20 minutes (Jimenez et al., 2020; ThinkProductive, 2023).

Research on the topic shows a range of purposes for DH. ThinkProductive (2023) defines the content of the huddle as to check in on one another and outlining plans for the day, and to achieve alignment. The communication aspect of the huddle is also stated by Oladiran (2017) and Mastroianni and Abdelhamid (2003), who describe the purpose as improving the communication between the project manager and the foremen, resulting in a high level of commitment from workers on-site. Others report that DH meetings are used in construction to develop and improve assignments (Salem et al., 2004) and to plan and coordinate tasks (Noorzai, 2022). Paez et al. (2005) further add that DH meetings look for immediate actions that ensure the completion of highly variable assignments. Fuemana and Puolitaival (2013) describe the DH as an important part of production planning and control, as the follow-ups on plans are accompanied by DH, where the team control, plan, and rearrange production to minimize waste. This is aligned with Jimenez et al. (2020), who describes that DH is applied to identify disturbances in the production flow to then rearrange tasks and minimize time losses. Time loss is by Kalsaas (2010) and Wandahl et al. (2021) linked directly to crew productivity. Thus, a causal link between DH and onsite productivity is present via the reduction of time waste.

Several studies report on the benefits of implementing DH. Salem et al. (2004) investigated the effect of implementing different lean construction tools and found that DH had the largest positive effect. In addition, they applied a survey among workers, where 67% reported that they found daily huddles to be value adding. Mariz et al. (2019) implemented DH in a civil engineering project and found that team involvement was a key factor in deploying daily management. Many problems were reported at the DH. Simple problems were solved with immediate team action and larger problems that needed further analysis were forwarded to the engineering team. Consequently, they reported that cost reduction of 7% was achieved. Johansen et al. (2021) reported from a project where, among other lean elements, DH was implemented. In this project, waste time was reduced by 19%. Noorzai (2022) described that the most effective lean technique to improve success factors in the construction phase is DH meetings.

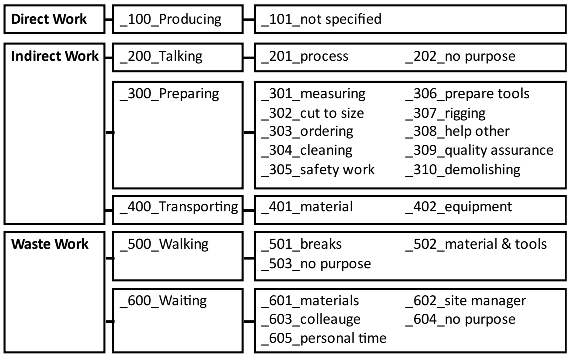
It is clear that DH is a part of the Lean philosophy and the Lean Construction application. Salem et al. (2004) argue that DH is part of the continuous improvement philosophy as it enables team members to improve collaboratively over time. Mariz et al. (2019) argue it can be viewed as part of the go-Gemba movement, as the site manager often conducts these huddles in the work zones or walks onto the construction site with the workers after the huddle. Several studies connect DH with the Last planner system, as DH focuses on achieving weekly planning for daily control through quick meetings with team members (Ballard et al., 2009). This view is aligned with Paez et al. (2005), who write, "*while Last Planner is a tool for managing operations, there is a need in construction for effective follow-up of highly variable events that affect assignments*" which then is referred to as the DH.

METHOD

The data collection is based on detailed Work Sampling (WS) as described in Salling et al. (2022). The WS technique has been used for decades to collect data on the amount of value-adding work time, often referred to as Direct Work (DW) (Gong et al., 2011). WS is a quantitative approach deploying direct observations to obtain data on craftsmen's time consumption on the construction site. In general, WS has been applied throughout time to improve single construction projects regarding efficiency, construction labor productivity, and construction cost and time. In this research, WS is applied both on the crew and on the site manager responsible for the crew. It is conducted with two different categorizations of observations. Moreover, as outlined by the research question, the data collection is narrowed to only collecting data in the first two hours of each day.

WORK SAMPLING – CREW

Step one is to clarify the categories of the activities to be measured: in this empirical study, the activities can be direct work (DW), indirect work (IW), and waste work (WW). This study followed the classification of Salling et al. (2022) with six categories for DW, IW, and WW: (1) Production as DW; (2) Talking, (3) Preparation, and (4) Transport as IW; and (5) Walking and (6) Waiting as WW. For each category, subcategories are defined, representing the actual activities of the observed crew on the site. The observations were conducted by an observer following the site crew and for every 1-2 min noting what each worker of the crew was doing including four types of information: a timestamp, a location, the work category, and the subcategory from the activity list shown in Figure 1, left side. The observer used an electronic form in Excel to collect the data (Figure 1, right side).

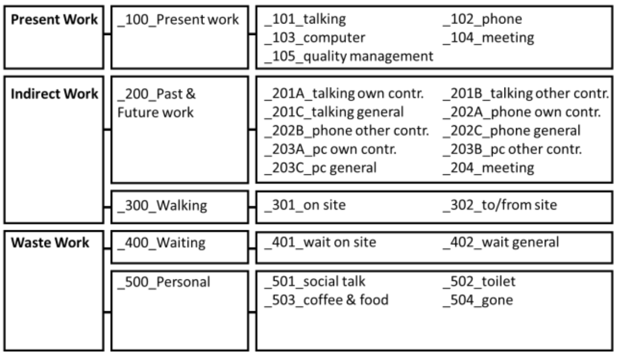


Number	Time	Category	Activity	Comment
1	07.01.03	_200_Talking	_202_no purpose	
2	07.03.59	_500_Walking	_501_breaks	
3	07.04.22	_200_Talking	_201_process	
4	07.04.35	_500_Walking	_501_breaks	
5	07.04.56	_200_Talking	_201_process	
6	07.05.03	_400_Transporting	_402_equipment	
7	07.05.37	_200_Talking	_201_process	
9	07.06.49	_300_Preparing	_310_demolishing	
10	07.08.49	_200_Talking	_201_process	
11	07.08.53	_300_Preparing	_310_demolishing	
12	07.09.46	_500_Walking	_502_material & tools	
13	07.09.59	_400_Transporting	_402_equipment	
14	07.10.16	_500_Walking	_503_no purpose	
15	07.10.37	_400_Transporting	_402_equipment	
16	07.10.49	_300_Preparing	_310_demolishing	
17	07.11.10	_200_Talking	_201_process	
18	07.11.25	_300_Preparing	_310_demolishing	
19	07.12.16	_300_Preparing	_310_demolishing	
20	07.12.34	500 Walking	502 material & tools	

Figure 1: Left: Taxonomy of categories; Right: Example of crew observations.

WORK SAMPLING – SITE MANAGER

Very little research has been published on work sampling for site managers. Therefore, the authors developed a new taxonomy that suits the purpose of investigating the effect of DH. Several pre-studies were conducted to identify the most suitable taxonomy. First, the two case site managers were interviewed to understand their work. Based on this information, it was decided that the taxonomy should include a time dimension, i.e., whether the task of the site manager focused on past or future work (categorized as IW) or on today's work (categorized as Present Work (PW)). Second, a pre-observation round was conducted on case 1, and the results were discussed with the site manager. Thereafter, the final taxonomy, as depicted in Figure 2, was decided. The observations were conducted using the same procedure as for the crew observations.



No	Time	Contract	Category	Activity	Location	Comment
44	07:22:15	1-Own	_100_Present	103-Computer, mobi	Office	
45	07:22:35	2-Other	_200_Past&Future	201-Tale	Office	
46	07:23:06	1-Own	_200_Past&Future	203-Computer, mobi	Office	
47	07:23:57	2-Other	_200_Past&Future	201-Tale	Office	
48	07:24:13	1-Own	_200_Past&Future	201-Tale	Office	
49	07:24:54	1-Own	_200_Past&Future	203-Computer, mobi	Office	
50	07:25:21	1-Own	_200_Past&Future	203-Computer, mobi	Office	Holidayscheme
51	07:26:05	1-Own	_200_Past&Future	203-Computer, mobi	Office	
52	07:26:27	2-Other	_200_Past&Future	201-Tale	Office	
53	07:26:38	1-Own	_200_Past&Future	201-Tale	Office	
54	07:27:02	1-Own	_200_Past&Future	203-Computer, mobi	Office	Holidayscheme
55	07:27:27	1-Own	_200_Past&Future	201-Tale	Office	
56	07:27:58	1-Own	_500_Personal	501-Social snak	Office	
57	07:28:30	1-Own	_400_Waiting	402-Vente	Office	PC loading
58	07:29:24	1-Own	_100_Present	103-Computer, mobi	Office	
59	07:29:48	1-Own	_300_Walking	301-Til byggepladser	Site	
60	07:30:21	1-Own	_300_Walking	301-Til byggepladser	Site	
61	07:30:56	1-Own	_300_Walking	301-Til byggepladser	Site	
62	07:31:40	1-Own	_300_Walking	302-På byggepladser	Site	

Figure 2: Left: Taxonomy of categories; Right: Example of site manager observations.

This study collected data for 5 days and used a 95% confidence interval. The guideline of CII (2010) was followed to calculate the minimum number of observations needed to obtain the confidence interval based on the number of workers in the crew. This was calculated for each of the two cases and for crew observations and site manager observations, respectively.

CASE ONE – NO DAILY HUDDLE

The construction project is a combined renovation and extension of a commercial and residential building in the centre of a large city in Denmark. The contract form is a general contractor, and the project has a budget of 6 million EUR. The project started in 2021 and is expected to finish medio 2023. The subjects for observation were the carpenter crew and the site manager responsible for the crew from the general contractor. The carpenter crew consisted of 4 workers, and the observed tasks were mainly flooring, installing windows, and gypsum panel installation. The site manager's approach did not include any lean methods and was mainly reactive as opposed to proactive with regard to the crew.

CASE TWO – DAILY HUDDLE

The construction project was a deep renovation of a large campus facility with offices, lecturing rooms, and large genetic lab facilities, totalizing 11.000 m2, awarded as a general contract. The contract is 83 million EUR with a timeframe from 2021 until ultimo 2024. The subjects for observation were the carpenter crew (around 15 workers) and the site manager responsible for the crew. The contractor was the same company as in case one. Crew tasks were mainly roofing work, mounting doors and windows, and gypsum panel installation. On this project, the site manager was very proactive and engaged in the crew's work. He facilitated DH every morning in the site office. The duration was 10-15 minutes, with the following topics: follow up on yesterday's work, talking about today, organising materials, informing about changes, etc.

RESULTS

In the following, WS data will be presented for each case respectively.

CASE ONE – NO DAILY HUDDLE

In case one, the site manager did not implement DH. Table 1 describes the data collected during the one week of WS for the carpenter crew, and Table 2 shows the data for the site manager responsible for the carpenter crew.

Table 1: Work Sampling data for the carpenter crew

		Direct Work	Indirect Work			Waste Work	
$\bar{p}$	(%)	8.0%	72.2%			19.8%	
n		91	823			225	
		Producing	Talking	Preparing	Transport	Walking	Waiting
$\bar{p}$	(%)	8.0%	20.0%	41.0%	11.2%	14.5%	5.3%

Table 2: Work Sampling data for the site manager

		Present Work	Indirect Work	Waste Work		
$\bar{p}$	(%)	12.5%	74.0%	13.4%		
n		115	679	123		
		Present	Past & Future	Walking	Waiting	Personal
$\bar{p}$	(%)	12.5%	69.9%	4.1%	1.4%	12.0%

As learned from the tables, the DW of the crew and the PW share for the site manager are both relatively low. A DW share of 8% is not uncommon but low compared to other studies. Wandahl et al. (2021) investigated 474 cases of work sampling data in construction, and only 2% has a DW share of less than 10%. The carpenter crew has a very high share of IW, 72.2%. In other words, the crew spends more than 2/3 of their time to understand, prepare and make ready to produce. In the same time frame, i.e., the two first hours of the working day, the site manager spends more than 2/3 of his/her time on work activities concerning past work, like claims and quality management or future work, such as planning, coordinating, or purchasing. He spends 12.5% of his time on today's production. Table 3 shows the most frequent subcodes in the observations.

The crew has most observations of talking about the process (16.3%) and measuring (7.73%). This clearly indicates that there are parts of the production which is not clear for the crew.

Table 3: Most frequently observed activities for the crew and the site manager.

Sub codes for crew		Sub codes for site manager	
_200_Talking_201_process	16.3%	_200_past/future_201A_talk own	3.05%
_200_Talking_202_no purpose	3.69%	_200_past/future_201B_talk other	8.29%
_300_preparing_301_measuring	7.73%	_200_past/future_201C_talk general	11.9%
_300_preparing_302_cut to size	7.55%	_200_past/future_202A_phone own	1.20%
_300_preparing_304_cleaning	2.55%	_200_past/future_202B_phone other	4.91%
_300_preparing_305_safety work	5.88%	_200_past/future_202C_phone gener.	6.76%
_300_preparing_306_prepare tools	5.00%	_200_past/future_203A_pc own	1.96%
_300_preparing_307_rigging	3.51%	_200_past/future_203B_pc other	1.42%
_300_preparing_308_help others	2.19%	_200_past/future_203A_pc general	24.1%
_300_preparing_310_demolishing	6.41%	_200_past/future_2004_meeting	6.32%

For the site manager, the most frequently observed category was using the computer (24.1%). It is also clear that the site manager spends more time on other contractors and general topics than on own contracts, both for talking (cat. 201), phone (cat. 202), and computer (cat. 203).

Both Direct Work for the crew and Present Work for the site manager is stable after approximately 700 observations, and with good 95% confidence intervals. The confidence interval shows that for the carpenter crew, DW = 7.99 ± 0.97%. A DW interval of [7.02-8.96] has been observed from data point no. 651 and onwards. For the site manager's PW share (Figure 3, right), the confidence interval is equally good with PW = 12.54 ± 1.37%. A PW interval of [11.17-13.91] has been observed from data point no. 590 and onwards.

Average day curves illustrating the time distribution for the carpenter crew and the site manager are depicted in Figure 3 to show variation over time, and to identify possible trends.

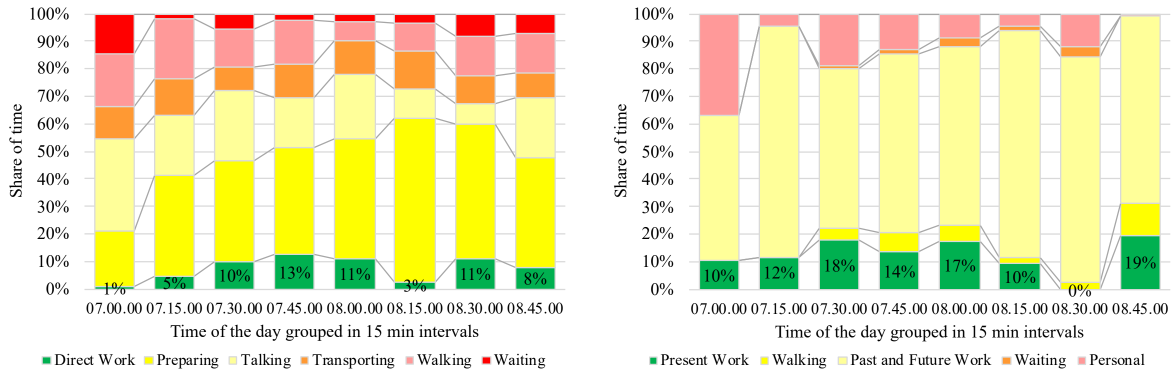


Figure 3: Left: Day curves for the crew; and Right: the site manager.

Figure 3 confirms the descriptive data from Table 1 and 2, showing that the performance, both in terms of DW and PW, is low. Moreover, two distinct patterns are observed. For the carpenter crew a pattern of DW starting very low at the beginning of the day and then slowly rising, is identified. The second pattern is seen on the curve for the site manager, who has a low and uniform distribution of PW. Most of his work time is spent on past or future work.

CASE TWO – DAILY HUDDLE

For case two, the site manager conducted DH every morning with the carpenter crew as described in the method section. Table 4 describes the work sampling data for the carpenter crew, and Table 5 shows the data for the site manager responsible for the carpenter crew.

Table 4: Work Sampling data for carpenters.

		Direct Work		Indirect Work		Waste Work	
$\bar{p}$	(%)	28.2%		56.4%		15.4%	
n		791		1584		431	
		Producing	Talking	Preparing	Transport	Walking	Waiting
$\bar{p}$	(%)	28.2%	16.0%	23.5%	17.0%	13.0%	2.3%

Table 5: Work Sampling data for the site manager.

		Present Work	Indirect Work		Waste Work	
$\bar{p}$	(%)	28.1%	61.2%		10.7%	
n		224	487		85	
		Present	Past & Future	Walking	Waiting	Personal
$\bar{p}$	(%)	28.1%	49.0%	12.2%	1.5%	9.2%

As learned from the two above tables, the DW of the crew and the PW share for the site manager are both high, and around industry average Wandahl et al (2021). The carpenters spend around 1/3 of their time on preparing and talking about the work before producing. The site manager uses 49% of his time on dealing with past and future work. Compared to case one, the site manager on case two uses three times as much time on walking. This is because he spends time on the construction site among the crew. Based on the detailed codes of the WS, Table 6 shows the most frequently observed subcodes.

Table 6: Most frequently observed activities for the crew and the site manager

Sub codes for crew		Sub codes for site manager	
_200_Talking_201_process	14.3%	_200_past/future_201A_talk_own	5.15%
_200_Talking_202_no purpose	1.71%	_200_past/future_201B_talk_other	11.8%
_300_preparing_301_measuring	6.91%	_200_past/future_201C_talk_general	0.00%
_300_preparing_302_cut to size	6.52%	_200_past/future_202A_phone_own	0.25%
_300_preparing_304_cleaning	2.64%	_200_past/future_202B_phone_other	1.76%
_300_preparing_305_safety work	0.43%	_200_past/future_202C_phone_gener.	0.00%
_300_preparing_306_prepare tools	5.31%	_200_past/future_203A_pc _own	26.1%
_300_preparing_307_rigging	0.64%	_200_past/future_203B_pc _other	2.26%
_300_preparing_308_help others	0.14%	_200_past/future_203A_pc _general	0.00%
_300_preparing_310_demolishing	0.68%	_200_past/future_2004_meetings	1.38%

As in case 1, the crew has most observations on talking about the process (14.3%) and measuring (6.91%). The most observed categories for the site manager are also similar to case 1; working in front of computer (26.1%) and talking about other contracts (11.8%).

Based on the data from Table 4 and 5, stabilization of both crew and site manager are analyzed. DW for the carpenter crew stabilizes after 2,000 observations and with a good 95% confidence interval. The high number of observations (compared to case 1) is due to the larger size of the carpenter crew. Direct Work ends with DW = 28.16 ± 1.80%. The PW category for the site manager is less stable. The Present Work share ends at PW = 28.14 ± 2.06%. Since observation no. 718, PW has been inside this confidence interval. Nonetheless, the data is considered valid and stable enough for further analysis.

Average day curves illustrating the time distribution for the carpenter crew and the site manager are depicted in Figure 5 to show variation over time, and to identify possible trends.

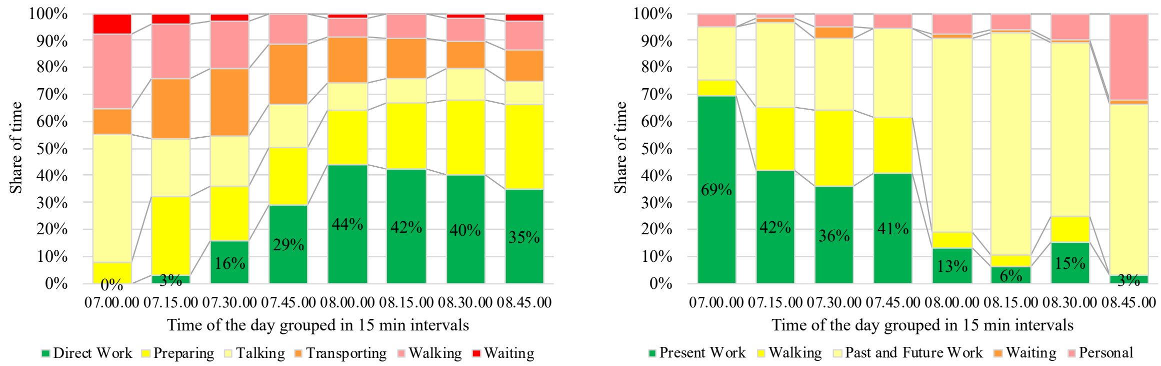


Figure 5: Left: Day curves for the crew; and Right: the site manager.

From the day curve of the carpenter crew (left side of Figure 5), it is visible that the workers take part in the DH from 07.00 to around 07.15. Their participation is registered as either preparing or talking (at the huddle meeting), depending on the crew is talking about work or talking in general. Some days, the Huddle was concluded faster than 15 minutes, whereafter the crew started walking and transporting material and tools to the production zone. For the site manager (right side of Figure 5), his engagement in DH is also visible. His participation in the DH is registered in the Present Work category. As mentioned, the huddle some days ended faster which creates indirect work from 07.00 to 07.15. After the Huddle, the site manager often walks to the construction site and joins the crew to assist and answer questions and address problems that might occur. After the first hour, the site manager typically concludes that work is running well (which can be confirmed from the DW=+40% from the crew), and he then starts planning for future work or follow-ups on past work, quality management, etc.

DISCUSSION

Case one and case two clearly show different results. Case two applied DH, and case one did not. Most interesting is the difference in how the site manager uses his time in the first two hours of the day, cf. figure 3 and 5. In case two, the site manager uses around 50% of his time to be productive and focus on present time activities. This is very different from case one, where the site manager uses 50% or more of his time on past and future activities and only uses 10-20% of the time on present activities. One reason for the difference is the DH applied every morning on case two. Another difference that provides insight is they sub activities the site manager is using his time on and how this is distributed over time. In case one, the site manager's time use is relatively uniform over time cf. figure 3, which is not the case for case two. Here the time use changes significantly during the day, cf. figure 5. In the first hour, the site manager uses around 50% of the time on today's activities, and after the first hour, the time use shift towards a focus on planning future activities and following up on past activities. The interesting result is that there seems to be a causal relationship between the site manager's time use and the crew's share of time on DW. This is most visible in case two. Comparing the left side (crew DW) of figure 5 with the right side (site manager's time use) shows an opposite pattern. This pattern is likely a consequence of the DH. The crew starts with a low DW, in fact, zero, because they use time on the DH. It is then seen that soon after the DH, the crew's productivity increases to a high and steady level.

The above results must be considered with some limitations. Firstly, only two cases are the basis for the result. This is insufficient to draw a scientifically valid conclusion, however, it indicates a clear tendency that is worth further investigating. However, this study has developed a methodology that allows for collecting more case studies to further examine the trend. The use of detailed WS increases the validity and paves the road for arguing for a causal relationship between DH and crew DW rates. A second limitation is that the analysis shows a delayed effect of the DH. This can be explained with a causal explanation, that improved production conditions will improve the share of time used on DW, however not instant. Conducting ad DH will not immediately improve crew share, the effect might be delayed. The results from case two show that the effect is visible after some hours, but the effect on the rest of the day is not investigated in this study, which calls for further investigation. A third limitation is that the DW share of the crew and the site manager cannot be isolated, with DH being the only variable. Other and unknown variables could influence DW shares, however, these variables cannot be excluded from the analysis. For instance, the effects of social constructs and trust, in general, will likely influence DW. A fourth limitation is that the two cases were very different in crew size, and the effect of large vs small crew cannot be isolated in this analysis. More studies with various crew sizes are needed. However, methodologically, crew size does not influence DW rates, or stabilization of DW, as smaller crew sizes just require a longer duration of data collection to achieve the same amount of data points.

The relevance and impact of this study are both related to academia and industry. For industry this research demonstrates the benefit of DH, even taking the above-mentioned limitations into account. Previous research has also concluded positively about the use of DH, however, few studies have succeeded in quantifying and measuring this cause-and-effect relationship. For research purpose this study can serve as a first run study on how to measure the effect of DH. The dissemination of the learnings from this study is of value for designing future studies on measuring the effect of DH. Moreover, DW data is not Construction Labour Productivity, however, DW is a valid indicator for Construction Labour Productivity as it shows the resource use, i.e., the denominator of the Construction Labour Productivity equation.

CONCLUSION

The objective of this study was to investigate the site managers' time use and its impact on crew productivity. For that purpose, the study conducted a review of both site managers and their time usage and on Daily Huddles, as one prominent approach for improving crew productivity. The review concluded that scarce research has focused on site managers and their impact on project success. Several studies report on the effect of Daily huddles, however, often the reports are based on logical arguments rather than data.

In continuation of the above, this research designed a method based on a case study to investigate the effect Daily Huddles has on crew DW shares. An adaption of the work sampling method to suit site manager data collection was designed and tested. The result of the two case studies, one with and one without Daily Huddles implemented, clearly show a difference in site managers time usage and crew’s share of time spent on DW activities. Conducting Daily Huddles seems to have a measurable effect on crew DW rates, even though the study includes some limitation.

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A COMBINED DIGITAL TWIN AND LOCATION-BASED MANAGEMENT SYSTEM

Manuel Jungmann[1], Timo Hartmann[2], Rahul Tomar[3], and Lucian Ungureanu[4]

ABSTRACT

As the coordination of resources' flow during location-based construction is complex due to limited space and simultaneous movements, management systems have been extended by adding a control stage to handle deviations from the initial schedule. However, a suitable information system has yet to be established. Therefore, a combined digital twin and location-based management system was developed. The digital twin concept relies on continuous, real-time data collection to provide information about the project's status. The combination of both methods facilitates effective, data-based production planning of the resources' flow over time and space. The proposed system offers the ability to proactively manage real-time information for ongoing location-based work through discrete event simulation. For improved understanding among stakeholders, the simulated processes are visualised in a 4D game engine. In an exploratory study, the system's effectiveness was demonstrated by using literature-based changes in productivity rates during the construction of finishing work in a high-rise building. The discrete event simulation results indicate that by ordering reasonable actions in response to construction deviations, a high level of resource efficiency can be maintained. This highlights the importance of using real-time data in location-based construction projects.

KEYWORDS

Digital Twin Construction, Discrete Event Simulation, Location-Based Management System, 4D Process Visualisation.

INTRODUCTION

As many different interacting trades are involved in the construction phase, appropriate coordination before and during the works is essential for successful sequences (Trebbe et al. 2015). A well-organised planning phase, which includes all stakeholders, before the construction start helps to reduce subsequent conflicts. However, during construction, unexpected issues arise, such as delays or disruptions, that lead to process deviations. Process deviations refer to any changes during production that deviate from the initial planned schedule and may cause time-space conflicts on site. During time-space conflicts, at least two activities must be executed simultaneously at the same location, which impedes continuous workflows (Akinci et al. 2002). The location-based management system is an approach used for efficiently

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planning trades' workflows to avoid clashes between participants. In comparison to previous location-based methods, the location-based management system extends the planning process by a controlling stage during construction. Currently, the control process is enabled by weekly planning meetings according to the Last Planner System® (LPS) (Seppänen et al. 2015). However, for efficient planning within weekly meetings and for managing ongoing construction works, reliable information regarding current site conditions and processes are required. Insufficient communication and information exchange among trades is a prevalent issue in current construction practice (Dallasega et al. 2018), which hinders efficient construction work and results in wasted time for staff. The digital twin concept can remedy these shortcomings, as it aims to provide data-based status information in real-time. It is crucial to use the information gained to proactively manage ongoing works through modelling and simulation while considering Lean Construction principles (Jiang et al. 2021). This approach is called digital twin construction (DTC) (Sacks et al. 2020). One essential aspect of digital twins is the appropriate visualisation in an intuitive and understandable manner (Rogagae et al. 2022).

In this paper a combined digital twin and location-based management system was developed (DTLMS) as an advanced method. By integrating DTC, the location-based management system benefits from continuous, real-time information regarding ongoing construction processes. Real-time knowledge can enable data-driven management of trades' workflows and more efficient construction execution. In a previous study, the authors demonstrated how machine learning classification can be used to extract reliable, stochastic activity durations from real-time data and calibrate a discrete event simulation (DES) model (Jungmann et al. 2022). This paper focuses on the usage of gained information in a DES to ensure efficient construction by investigating possible what-if scenarios. To support the planning, a 4D process visualisation tool was added to the system. The simulated construction processes are illustrated in a game engine for improved communication among stakeholders in planning meetings. The paper presents the DTLMS as a business process model and notation (BPMN) and aims to demonstrate efficient project planning according to process deviations in a case study. The paper is structured as follows: The following section presents a theoretical framework of the topics location-based management system, DES, and DTC. Next, the developed DTLMS is described by a BPMN followed by the application of the developed DTLMS approach on a finishing works case study. The final section summarises the findings, limitations, and future research.

THEORETICAL FRAMEWORK

Modelling and simulation is an effective method for supporting construction planning and control (Altaf et al. 2018) by efficiently testing different scenarios and their estimated impacts. DES has proven its usefulness in supporting the decision-making process in location-based production flow research (Brodetskaia et al. 2013) by investigating construction processes and resource allocations (Liu et al. 2015). DES can be used prior to the start of construction to determine the master schedule and during construction to generate and investigate control actions. To produce reliable simulations of process flows, DES requires meaningful input parameters that represent current productivity rates from the construction site. Therefore, it is essential to receive data about production processes during the construction phase to update input parameters according to current site conditions. To this end, a digital twin is required, which offers reliable data-based information in a timely manner. It is important to ensure that data-driven information integration adds value to production management (Dave et al. 2016). Real-time data enable the determination of reliable activity durations, which can be used within DES to plan location-based resource flows based on the simulation results. The results of the DES need to be visualised to enhance the understanding of the sequences and their impact on time, space, and resources. Traditional 2D plans are often difficult to understand in short meetings, but 4D visualisations enable a superior visual project representation (Crowther and Ajayi 2021). The different approaches – Location-based management system, DES, DTC, and 4D visualisation – complement each other and exploit the potential benefits of the combined system.

LOCATION-BASED MANAGEMENT SYSTEM

Location-based management methods focus on the flow of resources across different work zones provided by a location breakdown structure (LBS) of the construction site to support the planning process by considering time and space. Due to the adjustment of resource allocations, productivity rates of different trades become similar. Thus, continuous resource workflows over locations can be achieved and waste can be minimised (Seppänen et al. 2014). This method is particularly useful for repetitive construction works, but planning the distribution of resources over time and locations while avoiding idle time remains a major challenge (Ungureanu et al. 2019). A technique within location-based management systems is to delay the start of activities at the first location to consider a sufficient time buffer between tasks (Seppänen et al. 2014). For lean production planning, control, and the location-based management system, it is essential to visualise problems as early as possible (Seppänen et al. 2015). Within location-based management systems, flowline diagrams – a visual representation of crews' movement over time on the X axis and over locations on the Y axis – are used as 2D visualisations. A recent study demonstrated that a significant amount of time is wasted during mechanical, electrical, and plumbing work due to communication issues among workers caused by insufficient plans and schedules, as 2D plans are often confusing and unsuitable (Görsch et al. 2022). 4D models add a time dimension to digital 3D models, such as a BIM model, making them more intuitive for providing an overview and identifying project conflicts. Research has shown that 4D visualisations significantly improve the planning process and project reliability by facilitating collaboration among project partners (Crowther and Ajayi 2021). Hence, there is a need for research on 4D visualisation based on schedule simulation and automated progress monitoring (olde Scholtenhuis et al. 2016).

The location-based management system strives to manage deviations as early as possible to adapt trades' productivity rates in scheduling to prevent any time-space conflicts or adverse impacts on the construction execution. Changes in resource allocations could be applied as control actions (Seppänen et al. 2015). The LPS is a Lean Construction method that proposes weekly lookahead meetings to control current processes on a construction site (Ballard 2000). Therefore, location-based management system and LPS complement each other to improve production management during construction works (Kenley and Seppänen 2010). However, approaches for information flow between these two systems and its appropriate usage are needed. Thus far, discussions in lookahead meetings regarding changes in construction sequences have been based on separate, paper-based project documentations (olde Scholtenhuis et al. 2016) or the subjective experiences of different stakeholders who are often unwilling to compromise due to financial concerns (Ballard and Tommelein 2021), rather than site data (Hartmann 2021).

DISCRETE EVENT SIMULATION

DES enables the simulation of real-world events in a virtual environment. The effects of management-decisions and what-if scenarios can be modelled and investigated in a cost-effective and risk-free way (Wainer 2009). In recent years, DES has been increasingly employed in lean construction research (Shou et al. 2019) as a suitable method for handling the management of complex construction interactions by dividing the schedule into discrete events (AbouRizk 2010; Martinez 2010). DES simulates a list of separated events over time and the system's state changes according to the occurrence of discrete events. The simulation is proceeded according to a provided activity duration, which can be either deterministic or stochastic. Based on the activity duration, required resources are seized. If the required resources are already seized for another activity, the activity has to wait in a queue until the resources are released. Hence, DES enables the description of the resources' flow in a system. DES functions as an input-output transformer by taking input parameters and outputting process durations and resource usage. While the potential of DES is acknowledged in the construction sector, its usage is limited due to a lack of meaningful input data (Abdelmegid et al. 2020), resulting in unrealistic outputs (Abbasi et al. 2020). Nevertheless, Shou et al. (2019) provided a systematic review of DES application in lean construction research.

DIGITAL TWIN CONSTRUCTION

For the usage of a digital twin, it is essential to determine its purpose beforehand (Brilakis et al. 2019) as digital twin models have to be used for a target service (Jiang et al. 2021). In general, it can be stated that a digital twin for the construction phase consists of three elements: a physical system, a digital model, and its bidirectional data, information, and knowledge exchange (Tao et al. 2019). Real-time data are collected using different technologies, such as sensors or cameras, on the physical asset and sent via the internet to an Internet of Things (IoT) platform, where the data are accessible from everywhere. The collected data are analysed by artificial intelligence to gain information about current conditions. This provides reliable project status information (PSI) and the digital model, the digital twin, can be updated according to the physical system and knowledge is created by comparing the PSI with the as-designed building and the as-planned process. This results in project status knowledge (PSK). Precise PSI and PSK enable the use of the digital twin for data-driven simulation of ongoing construction works. The DTC paradigm is a mode to apply the digital twin concept for proactive management of production processes by considering lean construction principles (Sacks et al. 2020). In general, enormous positive potential is anticipated for the digital twin concept (Delgado and Oyedele 2021). However, the digital twin concept is still seldom applied in the building sector, especially in the construction phase (Sacks et al. 2020), although digital twins can promote smart construction. The implementation of digital twins in the construction industry is very complex, as many interacting resources move continuously on large-scale sites influenced by uncontrollable uncertainties. Therefore, there is an urgent need to develop common frameworks and demonstrate use cases for digital twins in the construction sector (Jiang et al. 2021; Pregnolato et al. 2022).

COMBINED DIGITAL TWIN AND LOCATION-BASED MANAGEMENT SYSTEM

A BPMN for the application of DTLMS by DES was developed (Figure). Before construction begins, a BIM file for the intended building is modelled. The BIM file is used to derive the required activities. The construction site can be structured into different zones according to a LBS so that for each zone information about required material amounts is available. By having different zones, the activities are structured in a work breakdown structure (WBS) for the management of the different tasks. Hence, due to the structuring into a WBS and LBS there is a final list of events, which is modelled in a DES. The productivity rates, which represent the activity durations, are derived of a historic database based on data collection from previous projects. Additionally, the number of resources needs to be stated. Within the DES, different options can be compared based on automatically calculated key performance indicators (KPIs). The following KPIs were determined: total construction duration, resource efficiency for the trades (i.e. the active time divided by the total time the trade is on site from the first day until the last day of work), idle days on the separate locations (i.e. the duration when construction works are not finished in a zone, but no works are executed in this zone), and total personnel costs for resources (the duration resources are on site multiplied by personal costs per day). It is aimed at achieving continuous workflows for all trades and avoiding time-space conflicts. If decision-makers decide on a construction option, the master schedule for long-term execution is stated. The before construction start available information from the BIM model, databases, and simulations builds the basis for creating the master schedule.

According to the master schedule, construction starts and sequences are executed. During construction, data collection technologies automatically collect real-time raw data and store it on an IoT platform. The data are analysed by artificial intelligence to determine the as-built and as-performed status, the PSI. E.g. time lapsed images can be taken and analysed by deep learning to track progress at certain intervals or sensors attached to the workers can provide data that are analysed by machine learning classifiers to track works. The PSI is used for control in comparison to the initial planning information. If deviations from the initial planning are detected, the productivity rates can be updated and stored in a database for use in following construction projects. Furthermore, this updated information can be input into DES to investigate realistic short-term what-if scenarios. The results offer the basis for managing ongoing works in the weekly lookahead meetings. Within these weekly meetings, it is aimed to maintain equal productivity rates for all trades to avoid idle time. If there is an urgent case, an earlier intervention than weekly is possible. The whole procedure is based on the plan-do-study-act (PDSA) cycle for continuous improvement of management processes. Due to the continuous data collection and the control actions, it is aimed to learn about processes and apply these gained findings for further improvement of the production sequence. This process must be repeated until all works are completed.

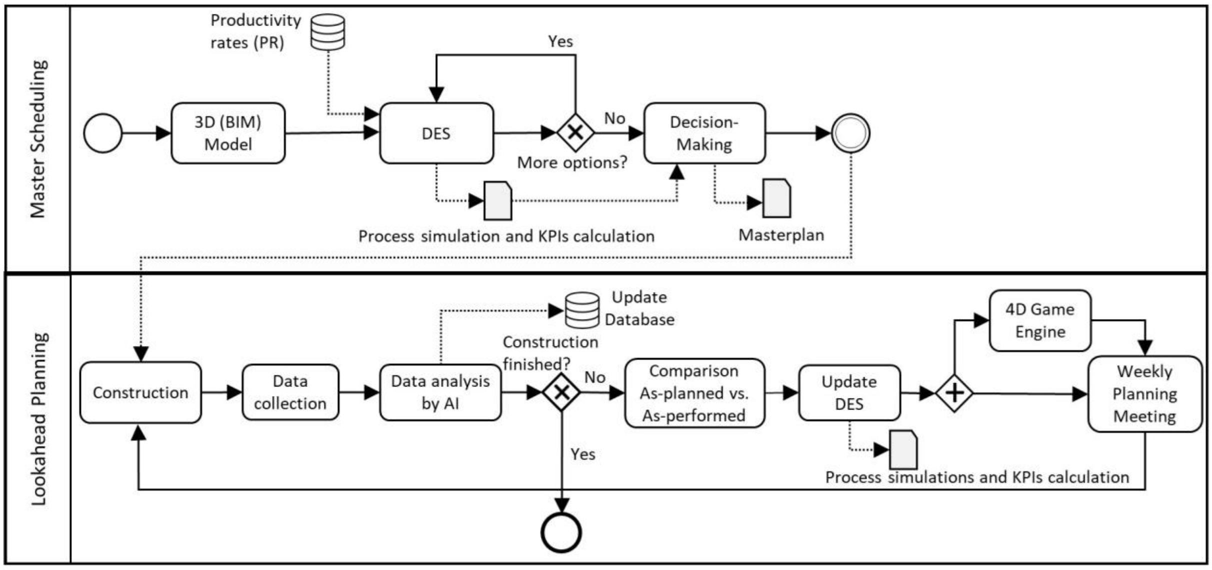

Figure 1: BPMN for a combined digital twin and location-based management system

A developed Digital Twin-platform, which is based on the game engine Unity, visualises the simulated processes of the trades. The BIM model as an IFC file is converted to a Unity file using a Python script to retain the geometry and metadata for import onto the platform. The start and end times for each process resulting from the DES are provided to the game engine as a JSON file. The information is interpolated to enable continuous process visualisations of the discrete events on the Digital Twin-platform. A colour is assigned to each trade and the construction site is divided into different zones. The zones are coloured according to the period during which an activity is executed by the trade. A Gantt chart timeline presents the activities at the bottom, which proceeds when the play button is clicked. Additionally, navigating back and forth is possible to investigate a situation in detail for better comprehension. By using a split screen, it is possible to compare the processes of different options next to each other.

DEMONSTRATION SITE

The demonstration site for the application of the developed system is a high-rise building in Gothenburg, Sweden. The future hotel and office building will have a total floor area of around 30,000 m². The floor area for each of the 27 floors ranges between 960 and 1,400 m². As most of the floors have similar floor plans, the finishing works will be executed in a similar sequence across all floors. The simulation of labour-driven operations executed by human resources, such as finishing works, is especially important, as the coordination is riskier due to the simultaneous execution by different trades (Bokor et al. 2019). A case study found that only 27% of the working time during equipment installation works is value adding and recommended research to minimise the wasting time (Görsch et al. 2022). Because finishing works are repetitive, it is possible to continuously learn from completed works and use the PSI and PSK for DTC management of ongoing works. The 16th floor, which will be used as a hotel, has a size of 1,200 m² and was chosen for an exemplary investigation (Figure).

Within this study, the execution of the following finishing activities by different trades was investigated: dry wall first side, wall installation of ventilation, plumbing, and electricity, dry wall second side, dry wall ceiling, painting, floor, and doors (Figure). The works are executed consecutively for each location by the following trades: dry constructor, heating, ventilation and air conditioning (HVAC), plumbing, electrician, painter, floor layer, and carpenter. Some activities require teams of two workers for the execution.

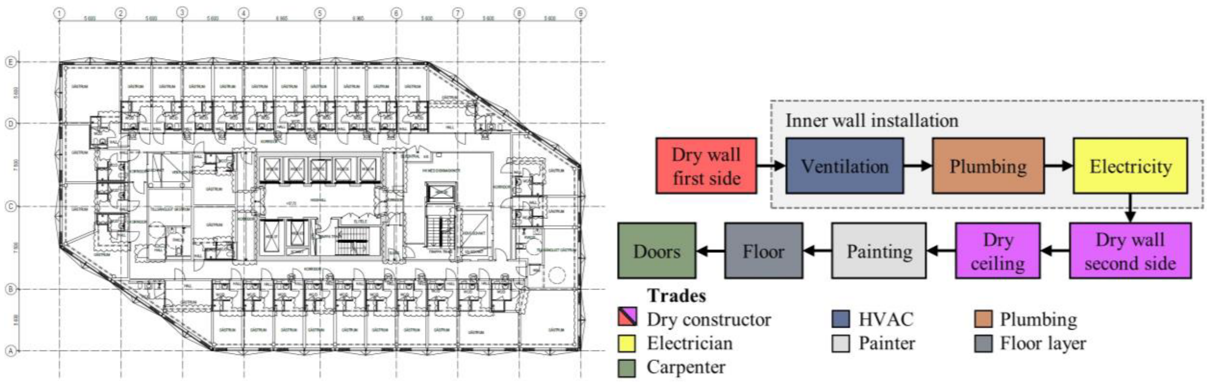

Figure 2: Floor plan 16th floor and process of finishing activities

APPLICATION

The execution of the finishing works for the 16th floor was modelled in a DES in R according to the process in Figure 2. The whole floor was divided into three zones of similar sizes. Due to the floor plan, the material quantities and the zone sizes differ slightly. According to the LBS and the WBS, there are 24 tasks as the dry wall work on the second side and the dry ceiling work were combined into one task. The productivity rates for each activity were derived from the construction company's provided schedule and the material quantities were gathered from the BIM file. The resulting activity durations were rounded up into whole days so that there would be a time buffer for the case processes proceeded more slowly than initially planned. If a higher number of resources is used, the execution of the activity is faster, however, at some point, there is a turning point and more resources hinder the execution (Ng et al. 2013). Therefore, a constraint of five simultaneous executed works of one trade in a zone was specified. To avoid time-space conflicts, subsequent activities can only begin after the previous activities are completed.

The stated KPIs were forecasted automatically in the DES to compare three different options. The two main principles of synchronisation – similar productivity rates among trades – and pacing – continuous process of activities across the zones – for location-based scheduling were integrated. As production management is especially complicated, if a trade returns to the same location (Brodetskaia et al. 2013), for the mounting of the second dry wall side and the ceiling, a second crew of dry wall constructors was introduced. Hence, one crew can focus on the mounting of the first dry wall side and the second team can work on the second side of the dry wall and on the ceiling. Thus, the whole sequence can be repeated subsequently on different floors. Option 1 is the initial planning before construction starts. Within Option 2, changed productivity rates during execution are considered, but no control actions are performed. Option 3 assumes the application of the DTLMS and the changed productivity rates are stated, followed by control actions to handle the deviations from initial planning. The results for the three options according to the DES are listed in Table 1.

Table1: DES results for different options

	Option 1	**Option 2**	**Option3**
Duration [days]	52	52	48
Efficiency trades [%]	100	100	100
Idle days on site	21	32	19
Personnel costs [€]	125,300	110,400	109,200

In Option 1, the resource allocations were adjusted before start to achieve continuous flows for each trade without any idle time. Therefore, the start of the plumbing trade was delayed by one day. Figure 3 presents the usage of the different zones. This results in an efficiency of 100% for all trades. Six floor layers working in two-person teams are commissioned and no idle time occurs, but the three zones are not occupied continuously. During construction, 21 days occur when no work is executed in one of the three locations, although the works have not been finished in the respective zone. In the first zone, there is almost no idle time, only the delayed start of the plumbing trade, but in the second and third zones, some several short-term interruptions occur. However, such short interruptions can also function as buffers, if a trade proceeds slower than expected. Option 1 results in a construction duration of 52 days and leads to personal costs of around 125,328€.

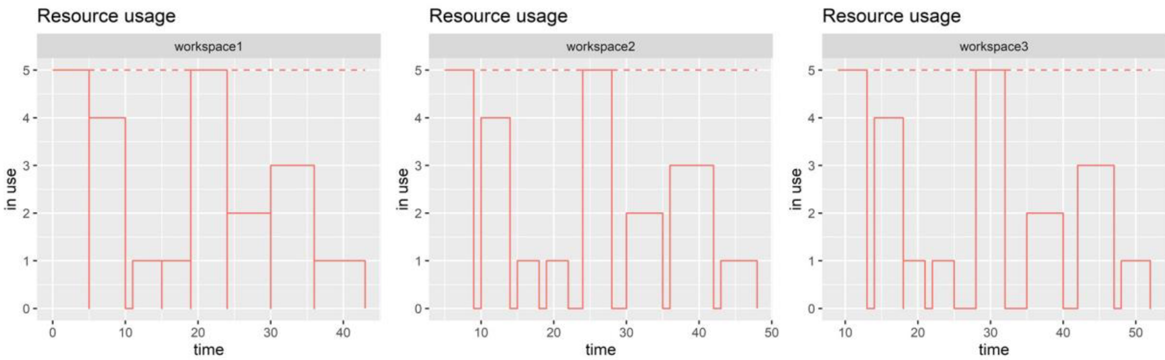

Figure 3: Option 1 - Zone usage

Option 2, the initial planning was based on Option 1, but a deviation in the actual productivity rate for the dry walls was assumed. The updated productivity rates were based on a study that investigated the productivity rates for dry wall work in a similar construction project in Sweden (Brosque et al. 2020), as no site measurements were possible. The mounting of the second side of the dry walls was faster in the construction company's assumptions, but the field investigation revealed that the construction of the first side was faster. The productivity rate for the first side changed from 0.200 h/m² to 0.106 h/m² and for the second side from 0.165 h/m² to 0.140 h/m². However, within Option 2, no change from the initial planning was made and the start date of the different activities was not amended. As the drywall work are executed faster, there is no change in the end date. Personnel costs fall slightly to around 110,400€ as the staff is required on fewer working days. No change in the efficiency of the different trades is observed, but the zones were used inefficiently as the duration of the idle periods increased as presented in Figure 4. On 32 days, no work was executed in one of the three zones, although the work in that zone was not completed. This is an idle time increase of more than 50% in comparison to Option 1. As the productivity rates for the first dry constructor team was faster, idle times occurs that sums up for all three zones. Additionally, the idle periods are of longer durations.

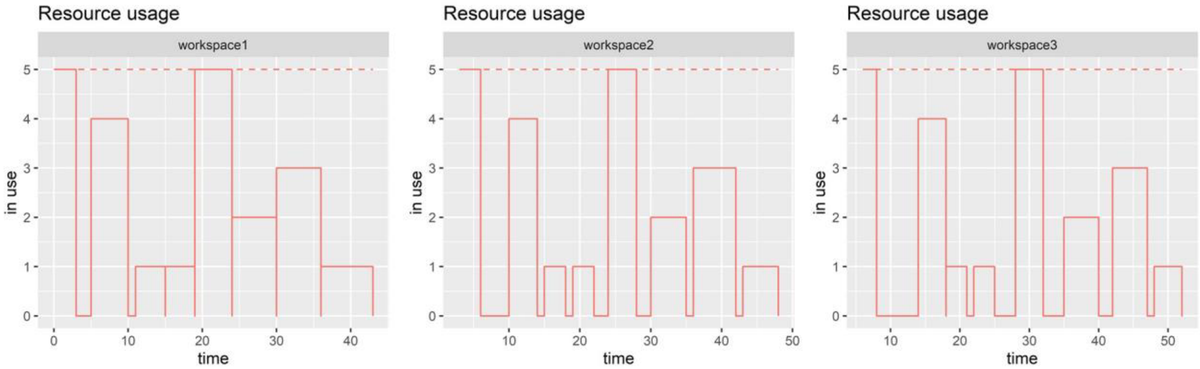

Figure 4: Option 2 – Zone usage

Within Option 3, it was assumed that the DTLMS was applied and the deviation of the productivity rates was stated by the digital twin concept. Subsequently, the gained PSI and PSK were used to adjust the initial planning and scheduling after the first week. On the one hand, the start dates for the following activities were brought forward. On the other hand, due to the faster productivity rate for the dry wall construction on the first side, another HVAC team was introduced to achieve a similar PR. As only a small deviation occurs for the mounting of the second dry wall side, this does not significantly affect the execution due to the simulation in whole days. Option 3 resulted in an estimated construction duration of 48 days. This is four days less than initially scheduled and the efficiency of 100% could be kept for all trades. Additionally, the idle days on the construction site were reduced to 19 days, an improvement of around 10% compared to option 1 and of more than 40% compared to Option 2. Figure 5 displays that the idle days were minimised and no idle days occurred in the first zone. The costs declined by around 15% to around 109,214€ compared to Option 1.

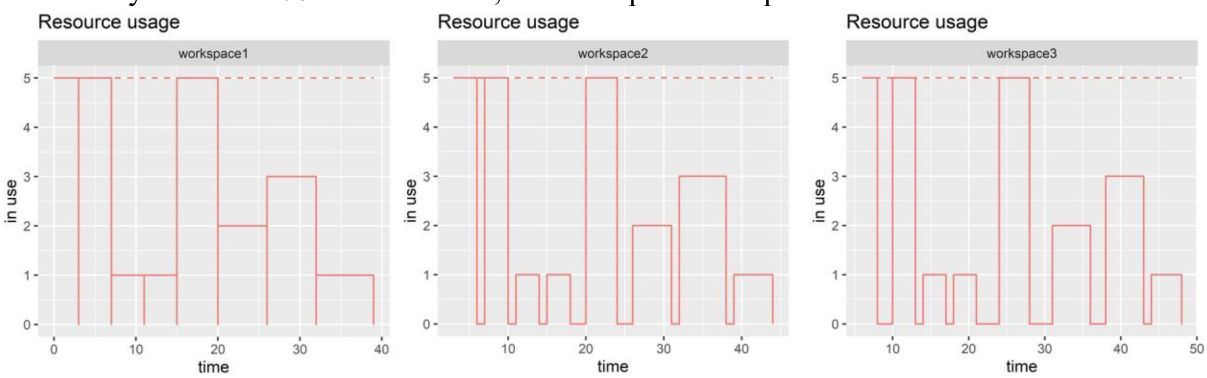

Figure 5: Option 3 – Zone usage

An image of the 4D process visualisation tool is presented in Figure 6. By clicking on arrow buttons, the different options can be selected. While the processes simulated for Option 1 are on the left side, the processes for Option 2 are visualised on the right side. The three zones are coloured differently depending on the activity performed and a Gantt chart provides an activity overview. Thus, the differences can be detected. By applying the developed approach, the impact of the construction execution can be improved in comparison to the initial planning. In all three options, a theoretical resource efficiency of 100% can be achieved. But in Option 3, the zones are used much more efficiently, as around 40% fewer idle days occur. Furthermore, the personnel costs could be reduced. If considering a larger case study and all floors of the investigated building, the positive impacts would increase even more.

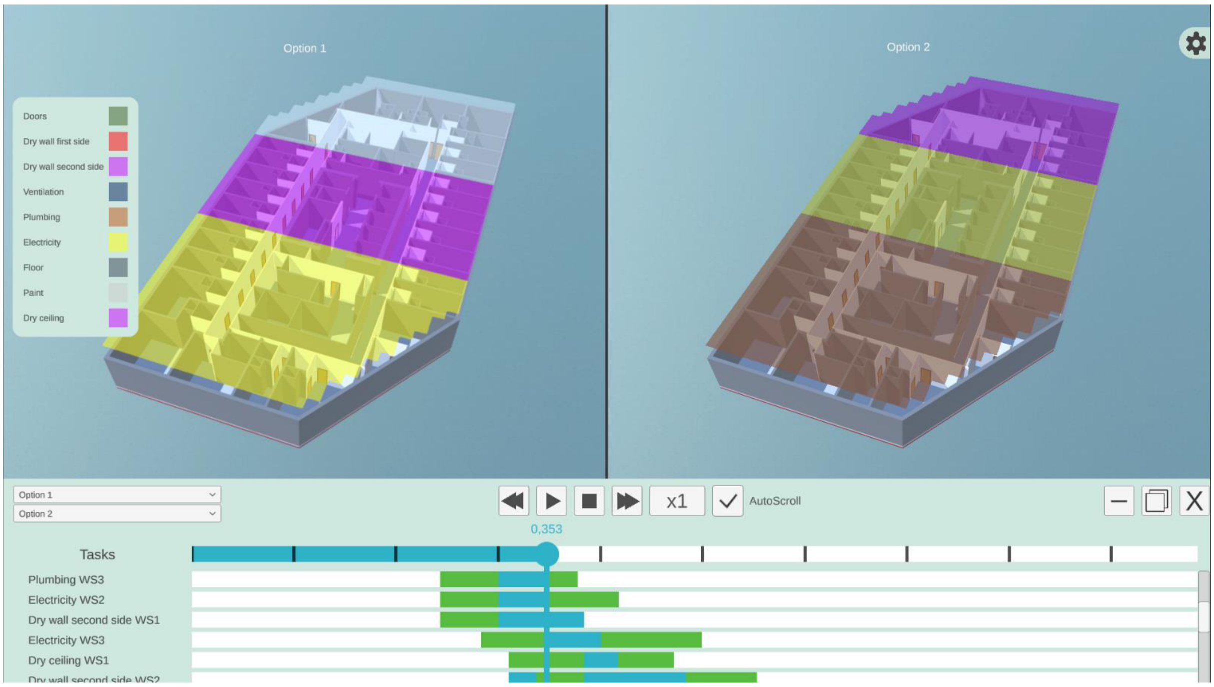

Figure 6: DES-based 4D process visualisations

CONCLUSIONS

The DTLMS presents a systematic approach for using real-time data during construction works for project management in consideration of Lean Construction. The paper provided evidence that using gained PSI and PSK can enhance the management of ongoing construction processes by ensuring continuous workflows and high efficiency during finishing works. However, in real projects, an efficiency of 100% remains a theoretical maximum (Ungureanu et al. 2019). Deviations from the initial master schedule should not necessarily represent an obstacle, but can also offer an opportunity to learn and improve ongoing processes. In the case study, it was possible to improve the estimated KPIs resulting in shorter durations, lower costs, and less idle time due to the intervention. The reason is the faster execution of dry wall work, which is uncommon in construction, as slower productivity rates are more frequently reported during production control (Seppänen et al. 2014). Nonetheless, this paper emphasises the need for real-time data-based construction control and, if necessary, control actions for handling deviations to hinder adverse impacts and shift away from subjective decision-making. The 4D visualisation assists due to an improved presentation of construction sequences and helps to identify conflicts in a timely manner. The extension of conventional 2D methods by the 4D process visualisation enhances the basis for discussion in weekly planning meetings. For successful management and execution, a common information basis and understanding of processes is required among all stakeholders, which also strengthens confidence.

A major limitation of this study was the use of literature-based measurements instead of data-based findings. The analysis of real-time data to gain reliable information for stochastic simulation was presented in a previous work (Jungmann et al. 2022). The focus of this paper was on the application of simulation for enabling control actions according to a literature-based deviation. Other than dry wall work, the productivity rates of different activities will vary from initial assumptions during construction. Hence, the investigation of an extended, more complex construction process will be expedient. Additionally, future research has to investigate the gap between the intended performance and the real performance, which will unavoidably differ. Future research should also consider the material deliveries via real-time data-based information in the DES to consider further uncertainties during construction. Furthermore, the game engine visualisations will be extended to a dashboard to enable information provision regarding past works.

ACKNOWLEDGMENTS

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PREDICTIVE SIMULATION FOR AUTOMATED DECISION-SUPPORT IN PRODUCTION PLANNING AND CONTROL

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ABSTRACT

Production system design, planning and control are limited both by the incomplete situational awareness of planners and by their inability to predict the range of possible outcomes of their planning and control decisions. With the development of information technologies for monitoring products and processes on construction sites, it is increasingly possible to provide detailed status information describing the as-built products 'as-built' and processes 'as-performed'. This opens the door to applying predictive analytics to provide decision-makers with frequent predictions of the outcomes for a range of changes they might contemplate to the production system design, even during construction. Within the BIM2TWIN project, we are designing and implementing an agent-based simulation engine that is a core component of an Automated Decision Support System. Currently, the simulation can be calibrated to accurately predict the range of likely project durations for a residential construction project. However, certain aspects of the trade crews' performance, particularly with respect to the completion of tasks, appear to differ from the behaviours described by industry experts and encapsulated in the crew agent behaviour tree in the simulation.

KEYWORDS

Production system design, production planning and control, agent-based simulation, decision-support.

INTRODUCTION

The design of a production system plays a critical role in determining its overall performance. A well-designed system not only ensures efficient production processes but also provides the foundation for effective planning and control. However, if the system's configuration is not optimal from the outset, even the most sophisticated planning and control techniques may not achieve the desired outcomes (Schramm et al. 2006).

The status quo in production system design (PSD) is that it is primarily performed until construction begins, at which point the production system configuration becomes largely static,

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and actions are limited to the scope of production control. This often leads to suboptimal solutions as the planners struggle to find the optimal configuration among the exponentially increasing solution space due to the large number of interconnected and interdependent variables at play. Without automation, planners must rely on known best practices, trial-and-error and their intuition and experience. This results in static production systems that are suboptimal with respect to the dynamic circumstances of construction sites, as opposed to the relatively stable environment of manufacturing plants.

An alternative approach is to apply automation to explore continuous optimisation of the production system configurations and parameters within the degrees of freedom of the system. This implies a shift from PSD as a planning exercise performed exclusively before construction to being an integral layer of production planning and control during construction. In this scenario, an automated decision support system (ADSS) would search the solution space to optimise the process, enabling the identification of multiple feasible alternatives. Additionally, it would provide forward-looking situational awareness (Lappalainen et al. 2021; Martinez et al. 2023), allowing planners to understand how the current production system configuration, as well as any alternative configurations, are likely to perform in the near future. Thus, planners could make better-informed decisions about the production system.

ADSS systems leverage the power of modern machines and information technologies to process data, optimise solutions, and analyse results (Bucklin et al. 1998; Payne 2000; Power and Sharda 2007). The core function of an ADSS is to predict the future behaviour of the production system based on its configuration and current status using digital simulation or statistical methods such as machine learning. The goal of an ADSS is to perform objective, comprehensive analyses of current and alternative production system configurations in very short times by virtue of automation, thus making continuous PSD through construction possible.

We present a novel predictive agent-based simulation framework for use within an automated decision support system (ADSS) for production planning and control. The framework is driven by 15 production system design parameters and generates 17 types of output data for performance evaluation. The capabilities of the simulation are demonstrated through the use of a real-world construction project in Finland, highlighting its current prediction capabilities and limitations. Furthermore, the paper outlines areas for improvement to further enhance the simulation's prediction accuracy and usefulness in real-world scenarios.

BACKGROUND

Automated decision-support systems (ADSS) are computer-based systems that augment decision-making by leveraging computer power to process data, make calculations, and generate information and knowledge to enhance situational awareness (Feng et al. 2009). ADSS can explore larger and more precise solution spaces than traditional trial-and-error-based planning approaches. This is achieved using advanced algorithms, such as mathematical optimisation, machine learning, and simulation, that can generate multiple solutions in a short period of time. With access to a large solution space, planners can identify feasible options, including some that may not have been considered previously, and select the most optimal for the project (Beynon et al. 2002; Marakas 2003). Thanks to automation, this can be done in much shorter times and with minimum effort (Gonzalez 2005).

Additionally, the use of computer algorithms helps ensure that solutions are not only optimal but also consistent, thus reducing the impact of human error and bias, which is especially relevant in the context of rapidly changing and uncertain construction environments. Future ADSS for construction may leverage data collected onsite, such as through digital twin and automated progress monitoring technologies (Kunath and Winkler 2018), to make evidence-based, explainable decisions that can improve the transparency and accountability of the planning process, as well as enhance trust and collaboration among project stakeholders (Coelho et al. 2021; Yeung et al. 2022).

Researchers have developed decision-support tools and systems for PSD. Draper and Martinez (2002) evaluated alternative production system designs for selected building construction processes with discrete event simulation (DES) to expose waste and artificial constraints hidden in the production system. Schramm et al. (2008) applied DES models in the decision-making process for the design and operation of house-building projects. The simulation models identified configuration options that reduced the total construction time. This, in turn, provided construction company production managers the ability to evaluate different scenarios and develop more efficient construction sequences, which led to a reduction in non-value-adding activities. Jadid and Badrah (2012) implemented a decision-support system for material selection based on value engineering to enhance interdisciplinary knowledge-sharing. These solutions have shown that proper decision-support systems can facilitate continuous improvement in all projects to improve their performance (Dave and Koskela 2009) and enhance the competitiveness of organisations with high absorptive capacity (Cohen et al. 1990).

Many existing decision-support systems use computer simulation as the mechanism for optimisation (AbouRizk 2010). Production systems in construction involve many heterogenous and interdependent components with stochastic behaviours, making it difficult to describe them with mathematical models without oversimplification (Abdelmegid et al. 2020). Simulation modelling allows for the description of a production system's components and their interactions, leveraging computer processing power to project and analyse the performance of the system. Additionally, a simulation can be used to optimise different aspects of the production system, such as resource allocation, scheduling, and process design, by changing the input parameters and observing the resulting output (Martinez 2010).

Of the main modelling approaches, agent-based simulation (ABS) particularly excels in producing explainable results (Bonabeau 2002). ABS uses a bottom-up, actor-oriented approach to represent systems as collections of autonomous agents interacting with each other and the environment. The interactions between agents give rise to emergent phenomena that can be observed at system-wide levels. Faithful reproduction of the behaviours of the individual agents within the system supports a comprehensive understanding not only of the overall system performance but also of the contributions of individual components (Macal 2016).

In recent years, researchers have applied ABS to investigate various aspects of construction production systems. Ben-Alon and Sacks (2015) developed the EPIC simulation tool to assess the impact of production control methods and information flow on production. Shehab et al. (2020) simulated construction crew performance using a hybrid ABS-DES model to facilitate weekly work planning in the Last Planner System. Barazi et al. (2021) proposed using ABS to study how parameter changes in vertical logistics systems can impact production performance in high-rise building projects.

SYSTEM DESIGN AND IMPLEMENTATION

The proposed system aims to assist planners in promptly exploring and optimising PSD at multiple points in a project by using project status and intent information. Specifically, by using parametric agent-based simulation, the ADSS can explore and evaluate a set of decision parameters, including changes in labour and/or resource allocations and in production control policies.

To design the system architecture, define the PSD decision parameters and outline the parametric agent-based simulation, we conducted a four-step process that included a literature review, gathering information from an expert panel, interviewing production planners, and observing and mapping agents' behaviours on construction sites. An expert panel of eight construction professionals from Finland, Spain, and France were consulted to specify the system features and functionalities. To define typical decision parameters used to make changes in production plans, we conducted 18 semi-structured interviews with production planners (Martinez et al. 2022). Through a behaviour mapping exercise on construction sites, we identified and mapped the behaviours of crews, supervisors, and site engineers in traditional building construction projects using decision trees. To design the overall system architecture, we applied a backward design approach and used a BPMN diagram to illustrate the system components and process flow, considering the functional requirements specified in the first step (Sacks et al. 2020).

The ADSS system comprises five main modules: 1) the User Input Module, 2) Simulation Module, 3) Alternative Plan Evaluation Module, 4) Alternative Plan Optimisation Module, and 5) Recommendation Dashboard Module. These modules work together to provide comprehensive decision support for construction production planning and control. The User Input Module receives the user's input information and selects the most suitable set of alternative production plans for simulation. The Simulation Module, designed according to agent behaviour specifications and implemented in AnyLogic® software, simulates the sets of alternative plans. The Alternative Plan Evaluation Module receives the raw outputs from the Simulation Module, evaluates alternative plan performance, and compiles decision aid elements and KPIs. The Alternative Plan Optimization Module enables users to generate additional alternative plans and simulation iterations based on optimisation algorithms. The Recommendation Dashboard Module presents the simulated production plans and their decision aids, allowing users to make informed decisions on the production plan to be applied in the next production cycle. The ADSS system includes two databases: 1) a Local Database that contains the baseline production plan, the constructed complete alternative production plans, their evaluation results and visualisation data, and 2) a Digital Twin Platform, which is a graph-based online repository for storing up-to-date project information.

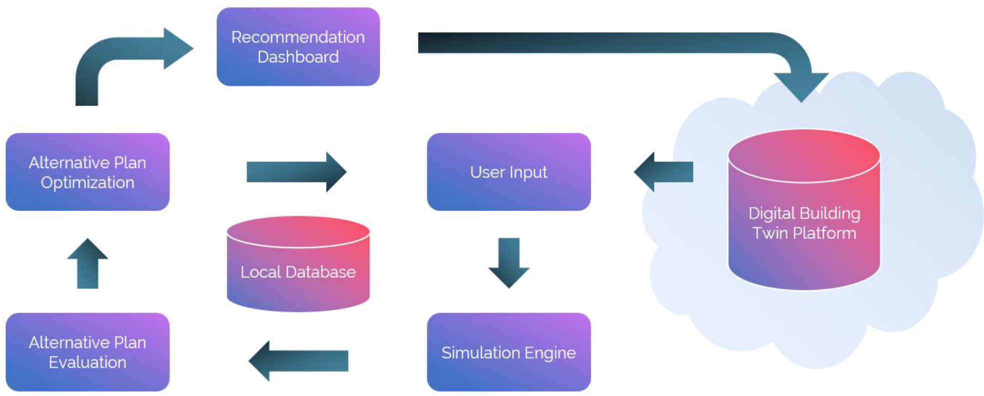

Figure 1: Overall System Architecture.

Table 1 details the 15 production system parameters that users can explore in the proposed ADSS. If a user decides to explore alternative production systems by modifying some of the parameters, such as adjusting crew sizes, the simulation engine can interpret the changes and apply them to the simulation before each run. In any given situation, there are multiple agents (managers, crews, equipment, materials, locations, suppliers, designers, etc.); each agent has multiple parameters, and each parameter can have some set of discrete values. For example, a 'drywall crew' agent may have a 'crew size' parameter, which may range from 4 to 6 workers. As such, the potential solution space is a complex product of the number of agents, parameters and possible parameter values. This yields combinatorially large numbers of production system configurations.

The predictive simulation engine in this ADSS uses the agent-based modelling approach. Agent-based modelling is a computational approach that simulates the behaviour of individual agents within a complex system. These agents have their own attributes, behaviours, and decision-making processes. They interact with one another in a decentralised fashion to create emergent system-level outcomes. In agent-based simulation models, agent classes are used to represent the general types of entities in a system, and specific instances of these agents are generated during a simulation run based on input data. This allows the model to represent the system at the individual level while also capturing the collective behaviour and interactions that arise between the agents.

Figure 2 gives an overview of the agent-based simulation engine's structure which includes the five classes of agents in the agent-based simulation model developed for this study: Work Crew, General Contractor Management (GC), Subcontractor Management (SC), Supplier, and Design Firm. The colour-coded rectangular boxes represent the different behaviours that each agent possesses, and the dotted lines show the interactions between these behaviours. This visual representation provides an overview of the behaviours and interactions of the different agents within the model and helps to understand how the system functions as a whole. For more details on the parametric generation framework, please refer to our recent paper (Yeung et al. 2022).

Table 2: Production system parameters.

Category	Parameter	Description
Labour	Production rate	The production rate for the specific crew (probabilistic-deterministic)
	Crew size	The crew size for each specific crew
	Number of crews	Add or remove a crew
	Crew calendar	Adjust the crews' calendars
Equipment	Maintenance rate	The equipment maintenance rate
	Number of equipment	Assign or remove equipment for a specific Work Package
	Equipment availability	Modify the availability time of equipment
Material	Material batch size	Change the material batch size for any material
	Material delivery frequency	Vary the material delivery frequency
	Material's buffer quantity	Vary materials' buffer quantities (percentage)
WBS	Task sequence	Change the task sequence
	Prerequisite tasks	Vary the prerequisite tasks
LBS	Construction site zones	Modify the construction site zones (Location-Based Schedule (LBS))
Production Control Policies	Material arrival strategy (pull or push)	Defines the material arrival strategy (push or pull)
	Work Package or location selection based on production planners' preference	The system gives priority to work packages where the largest quantity of productive work is available
		The system gives priority to spaces where work has already begun
		The crews assign the highest priority to spaces with the smallest amount of remaining work (Constant Work in Progress (CONWIP))
	Logistics Policy	The user changes the logistics supply chain type for a certain material

Each of the behaviours shown in Figure 2 was first defined in a behaviour map by construction experts and then coded as software routines in the simulation model. As an example, **Error! Reference source not found.** shows a behaviour map for the task assignment behaviour of the GC Management agent. A section of the corresponding logic tree in the AnyLogic software is shown in Figure 4.

Table 3 lists some of the result data that the simulation engine produces per simulation run. Each output is time series data, meaning that it is recorded at a specified frequency. This data is provided for each activity and resource, allowing diagnosis of the performance of the system at a fine-grained level. The abundance of high-resolution output data can be used to boost the ADSS's explainability to users, giving them confidence in the recommended solutions. It also enables calibration and validation of the simulation engine's prediction capability with high precision.

Table 3: Result data provided by the simulation engine.

Category	Output	Description
Trans-formation	Productivity	Work quantity completed per unit of resource input
	Resource Consumption	Quantities of material, equipment and labour effort consumed
	Earned Value	Accumulated value of work completed
	Project Progress	Percentage of work completed out of the whole project
Flow	Cycle Time	Amount of time it takes to complete a unit of product (e.g., apartment, floor)
	Throughput	Number of products completed within a given period
	Work In Progress	Amount of work in progress at a given time
	Non-Value Adding (Idle) Time	Amount of time a crew has been initiated but is not actively working on a task
	Space Conflicts	Number of times two or more crews require the same work location
	Material Buffer Size	Amount of material stored at a location at a given time
	Delivery Delays	Number of material deliveries delayed
	Equipment Capacity Utilisation	Percentage of total available time an equipment was utilised
Value	Material Delivery Date	Timestamp when a material order was fulfilled
	Resource Consumption	Quantities of material, equipment and labour effort consumed
	Rate of Rework	Percentage of tasks/products requiring rework
	Quality Control	Percentage of tasks/products containing defects
	Handover Date	Timestamp when a unit of product was handed over to the customer

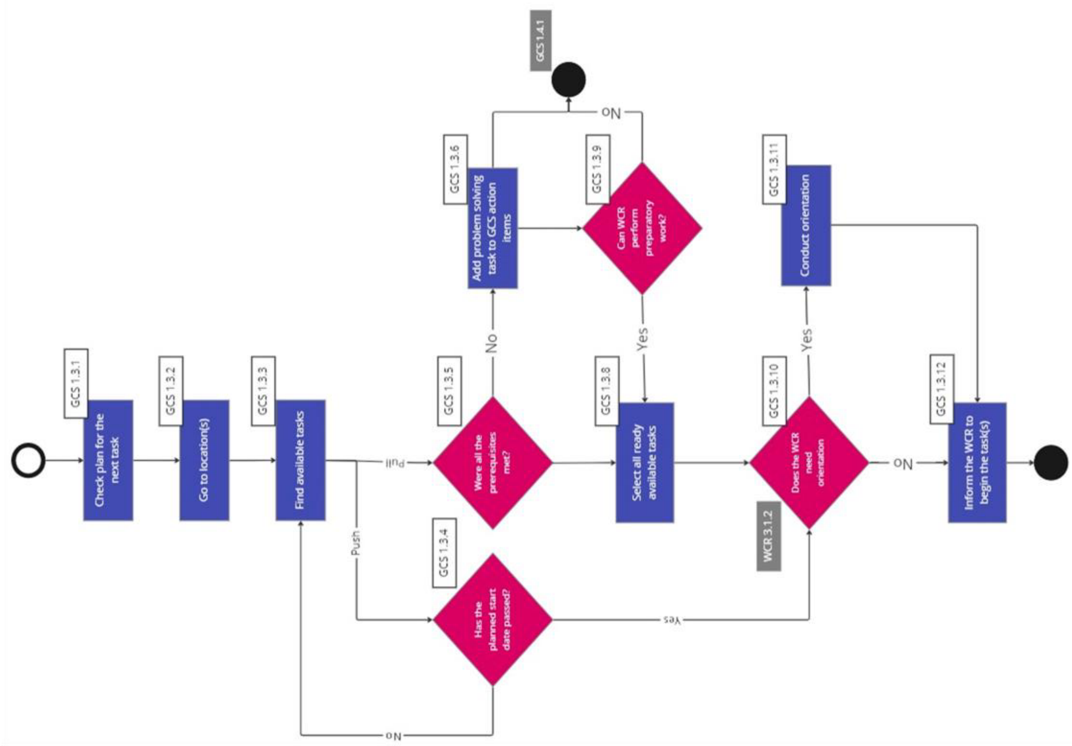

Figure 2: Behaviour map for GC Management task assignment behaviour as defined by experts.

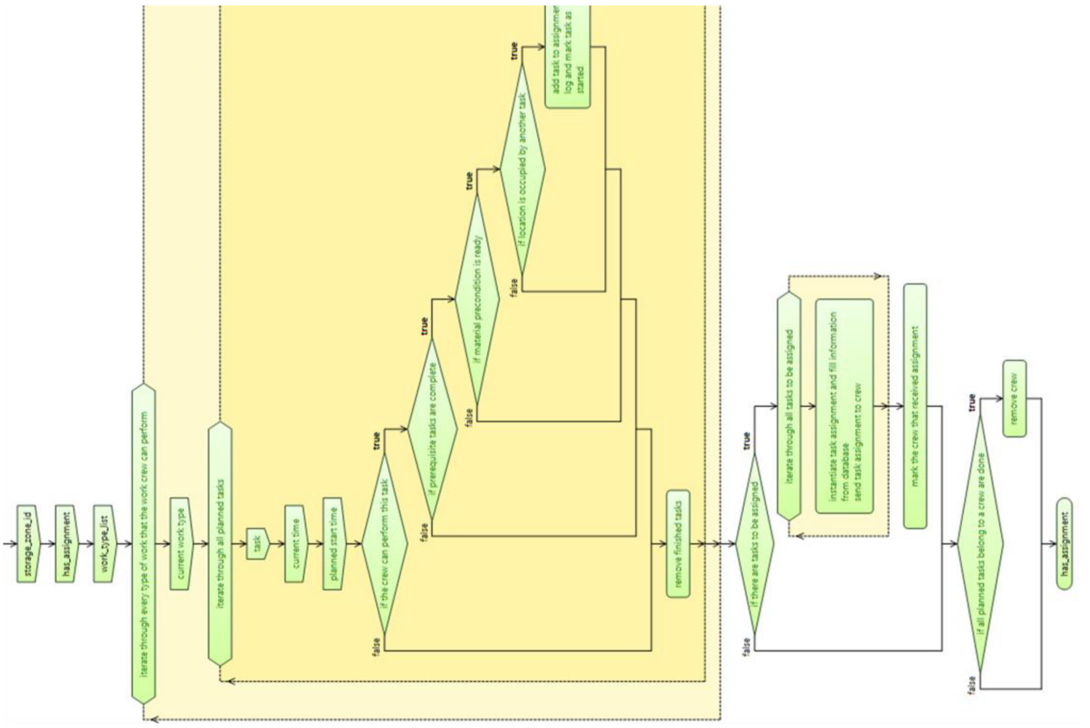

Figure 3: Behaviour map for GC Management task as programmed in the simulation.

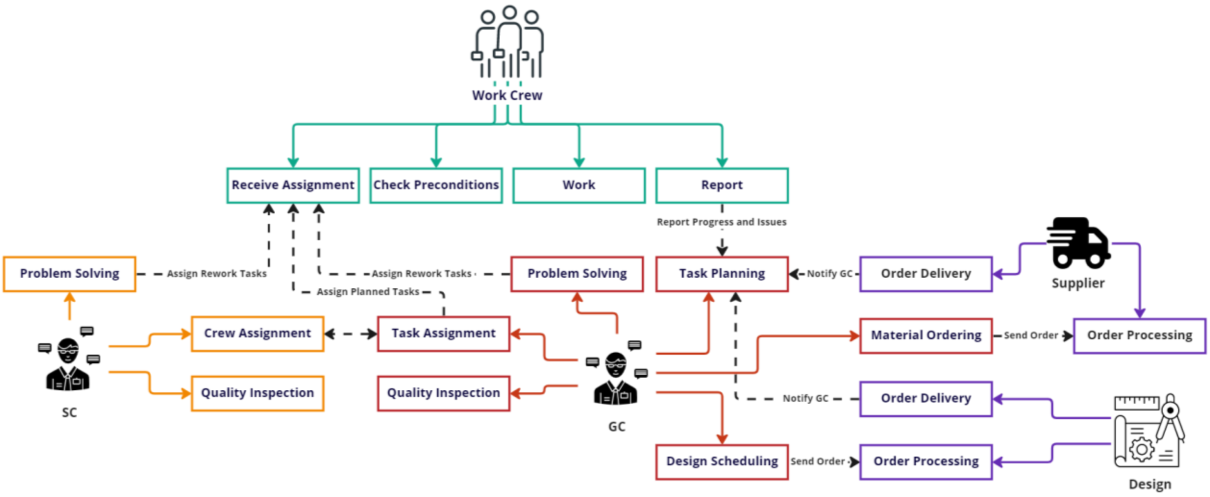

Figure 4: Agent classes and their behaviours in the ABS model.

CALIBRATION AND VALIDATION

To test and demonstrate the forecasting capabilities of the simulation engine, we apply it to an as-performed project dataset captured in a construction project of an eight-story prefabricated concrete residential building in Finland. The dataset covers the interior finishing phase of the project. It includes as-planned and as-performed progress, work quantities, planned production rates, a detailed work breakdown structure, and a location breakdown system. We used the progress data for validation and the rest of the data to set the initial production system parameters for the simulation. We ran 500 simulation runs using a Monte Carlo sampling method where the variance in supply chain reliability fluctuates randomly.

Figure 5 visualises the trajectory of project progress through time as a percentage of total tasks completed from the chosen start point (day 60 of the project). The as-planned progress curve is plotted in black, and the actual progress curve is plotted in red. The trajectory of each simulation run is plotted in a green spectrum, where lighter greens indicate earlier project end dates and darker greens indicate later dates. The figure shows a) that the actual progress deviated significantly from the planned schedule and b) that the actual trajectory falls within the range of the simulation's predictions.

Note that the planned trajectory lies at the left side of the distribution, suggesting that it was highly improbable, as would be expected in the case of a plan prepared using the Critical Path Method (CPM). This can be seen clearly in the histogram of project end dates presented in Figure 7. Here, we see that the actual end date and the planned end date are more than 30 working days apart, while the mean of the distribution of end dates is just ten working days earlier than the actual end date. The planned end date intersects the cumulative distribution curve at around 0.2 (i.e. a 20% probability of completing the project as planned).

Although the simulation results are promising in terms of projecting progress, a careful analysis of operational flow in these runs reveals that there is still much room for improvement in accurately simulating the actual flow patterns in real-world projects. Figure 8, a histogram of average cycle time per floor, shows that although the simulation results are closer to the actual results than are the actual outcomes for cycle times, they do not capture the actual patterns of flow. This discrepancy is also apparent in Figure 7, where the planned line of balance schedule is plotted against the actual status and against a representative simulation run. Towards the end of the project, there are multiple independent finishing activities scheduled in a tight time window. According to the actual record, these activities overlapped and intersected with one another in every location. In contrast, in the simulation run, the activities were performed in a relatively ordered way despite being scheduled tightly together.

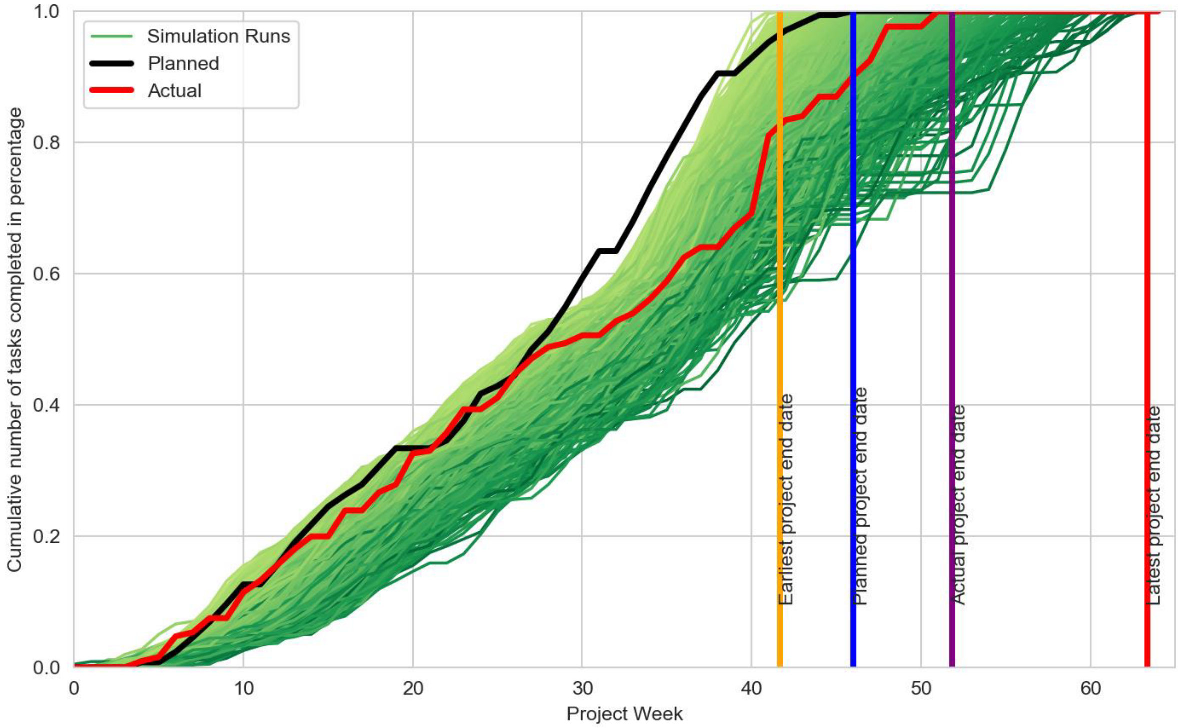

Figure 5: Progress trajectory of 500 simulation runs (green) plotted against the planned (black) and actual (red) progress.

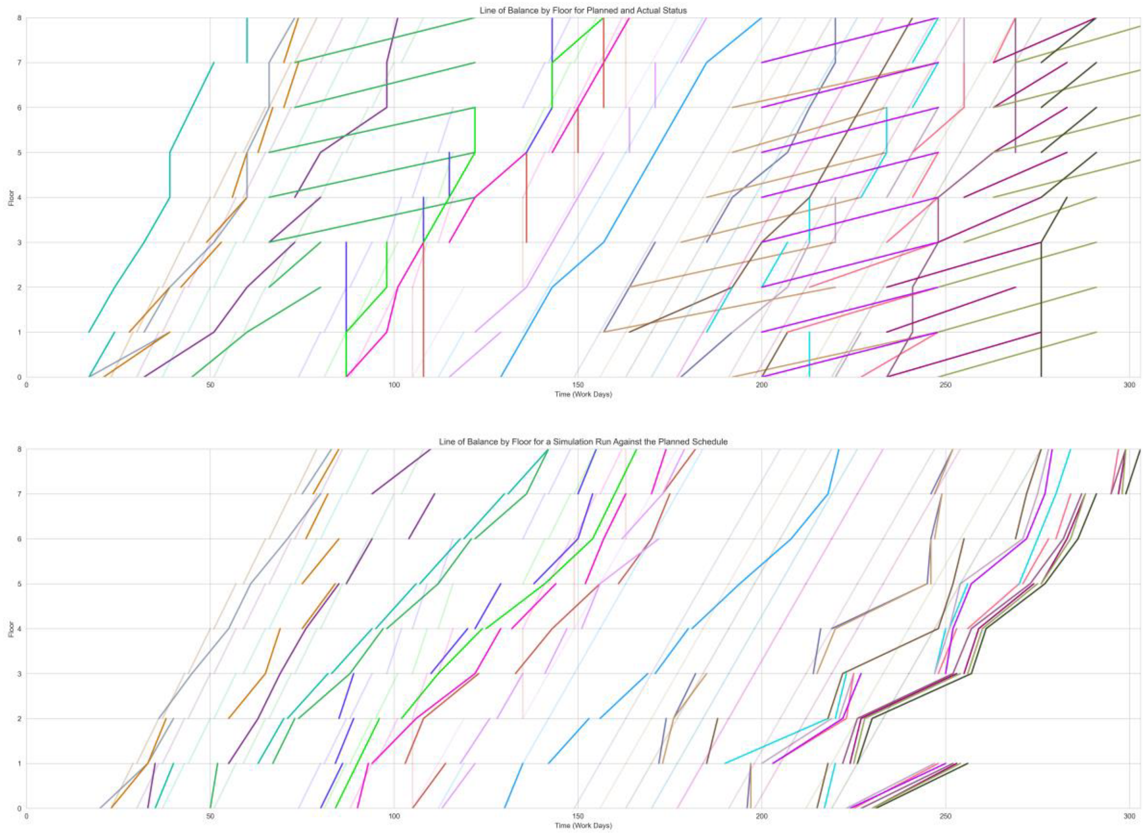

Figure 6: Line of Balance Charts. The top plot is the planned schedule versus the actual status. The bottom plot is the planned schedule versus a sample simulation run. In both plots, the as-planned schedule is plotted in semi-transparent colours.

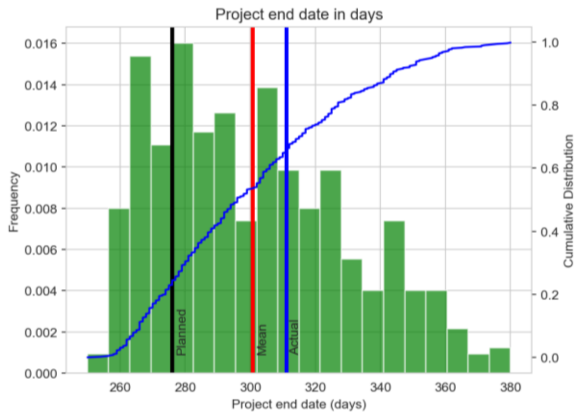

Figure 7: Histogram of project end date

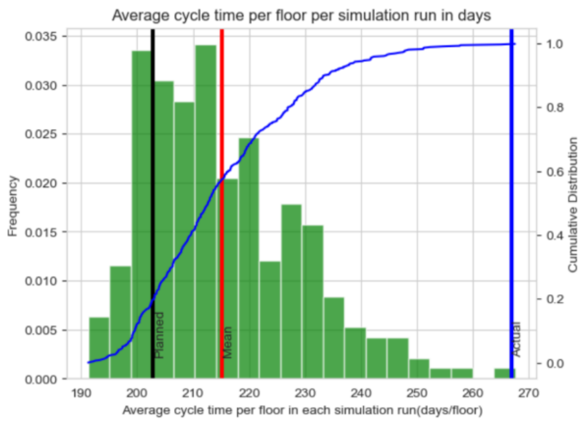

Figure 8: Histogram of average cycle time per floor

CONCLUSION AND FUTURE WORK

Automated Decision-Support Systems (ADSS) are essential components for adopting a broader view of production system design (PSD), extending PSD from a static, one-off design endeavour to a dynamic process of continuous improvement with optimisation. An automated ADSS can potentially help production planners explore the full feasible solution space to find optimal, evidence-based decisions in very short response times, making PSD a feasible exercise within the scope of lookahead production planning, and even weekly control, during the construction phase. The core function of such an ADSS is a predictive simulation engine that can project the probable future behaviour of a production system given its configuration, its current status, and the behaviours of its agents.

The paper detailed the input, output, and overall structure of a predictive simulation engine for an ADSS that is part of our ongoing effort to build such a system within the context of the BIM2TWIN project (BIM2TWIN 2021). Although the simulation can, at present, generate predictions of project duration that are a very good fit to the actual record of a validation project, a closer analysis of the results reveals that important discrepancies between the simulation results and the actual patterns of operation flow behaviours remain. This appears to be the result of discrepancies between the ways in which construction professionals at all levels understand and thus describe their behaviours and the ways in which they actually behave. This manifests in particular when crews complete the majority of the work in a given task or work package, but leave the final details unfinished, resulting in multiple instances of re-entrant flow in the actual record, and long cycle times for apartments, for example. Work remains to refine the behaviour of the agents to reflect this behaviour and to identify the production system parameters under which it occurs.

ACKNOWLEDGEMENT

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LOGISTICS PLANNING WITHIN THE LAST PLANNER SYSTEM FOR HIGHWAY CONSTRUCTION PROJECTS

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ABSTRACT

This study presents a new Logistics Planning methodology implemented in a highway construction project from May to December 2022. The objective was to analyze the feasibility of using a Logistics Planning method with the help of a Visual Board, in conjunction with the Last Planner System. The research method utilized was the Design Science Research. A 6-step method was developed to enhance the Lookahead Planning routine. After the implementation of the methodology, a decrease in the total and equipment-related impact hours in the productivity fronts was observed, as well as an improvement in the PPC indicator and labour productivity in each service front. It was concluded that the use of Visual Management, combined with Logistics Planning, stimulates the engagement of the operation's employees around the project schedule, increasing the accuracy of the Master Plan.

KEYWORDS

Lean construction Highways, Last Planner System, Visual Management, Lookahead Planning, Logistics Planning.

INTRODUCTION

Ever-shrinking margins and ever-increasing high-performance goals prompt construction companies to adopt the lean methodology in their construction sites (Tezel et al., 2018). Among all the tools within the Lean Construction methodology, the Last Planner System (LPS) stands out and aims to help in the implementation of Lean concepts in construction sites. Its goal is to create mechanisms to increase schedule reliability (Ballard & Tommelein, 2021). LPS seeks to transform long-term activities (what needs to be done) into medium-term activities (what can be done) by eliminating production restrictions and providing a bank of activities ready to be

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executed in weekly work plans, thereby generating confidence in the outlined action plan (Ballard, 2000).

In the building construction sector, a wide range of papers aimed at the adoption of LPS can be identified. The same, however, does not occur in the context of Highway construction, as the study of the planning and control system applicability is still in early stages.

Given the above, the objective of this paper is to analyze the feasibility of using a logistics planning method with the aid of a Visual Board, aligned with LPS. The hypothesis that this study sets out to test concerns understanding that the possibility of using Visual Management, combined with logistics planning, would stimulate the engagement of field teams in the lookahead planning, thus increasing the ability to identify constraints and the resource planning. The methods used in a specific case study and the results found are explained below.

LITERATURE REVIEW

In order to better understand the application of the Logistics Planning within the Last Planner System in road construction projects, the state of the art was sought in the International Group for Lean Construction (IGLC) database. On January 3rd, 2022, the keyword "Highways" search resulted in 17 articles. The vast majority of the scientific articles published on the page refer to the development of a Lean Construction implementation project aimed at English highways, called Highways England.[8]

Highways England is a government initiative that aims to improve the overall performance of the supply chain and meet the performance goals and cost reduction targets established by the government of the United Kingdom (HE - Highways England, 2018). The Lean implementation pilot project was developed throughout 2006, culminating in the paper published by Ansell et al., in 2007. The authors analyzed production constraints, measured the number of weekly planned and completed activities, and analyzed the root causes of non-fulfillment with the scheduled tasks through routines and tools based on LPS. Furthermore, they noticed that only 3.6% of the short-term planned activities coincided with the activities set out in the long-term planning, demonstrating little assertiveness of the Master Plan.

Subsequent studies aimed at addressing the reasons for non-compliance and low accuracy of the long-term schedule, as inferred from Fullalove (2013), and the improvements perceived from a more collaborative planning, such as the Last Planner System (Drysdale, 2013). From the identification of these early works on the low engagement of collaborators around the implementation of Lean, subsequent projects aimed to bring new elements that could help with this problem, such as Visual Project Management (Tezel et al., 2016) and the implementation of continuous improvement cells in the highway sector (Tezel et al., 2018a).

Although the aforementioned studies address tools and routines based on Lean Construction, such as LPS, Continuous Improvement, and Collaborative Planning, several studies have found that there is a need for more visual management on the work fronts to increase engagement with field teams. Thus, it is necessary to conduct a preliminary study of the specific needs of each project to avoid the risk of implementing these tools without a clear purpose (Tezel et al., 2018b).

According to Dahlberg and Drevland (2021), the delay in the delivery of materials, equipment, and tools is the main cause of production delays. Dawood et al. (2010), analyzing earthworks operations, share a similar view, pointing out that poor resource planning (materials, equipment, and tools) and low productivity are among the main factors for increased costs and

[8] Of the 17 articles found, 13 were published by authors from the United Kingdom, 9 of which were the result of the Highways England project. The other articles found will not be extensively analyzed here, since they do not relate directly to this research topic.

schedule overruns. Thus, the logistics and dimensioning of resources within the construction site must be planned in order to assist in the flow of balanced production.

Visual information can be an excellent strategy to assist in resource planning and logistic planning, alleviating a gap in the Last Planner System (LPS) and facilitating the visualization of constraints, leading to higher engagement from teams in collaborative meetings. In recent years, there has been an increase in the number of Visual Management (VM) studies in civil construction. However, the visualization of these effects is still done in a conceptual way. Within the context of highways, the study of using Visual Boards is still incipient, with few empirical studies (Tezel et al., 2016b). From the best of the authors' knowledge, the connection between logistics planning and VM is barely explored in the literature.

It is noted that, in the context of highways, visual information is generally limited to health and safety indicators. Nonetheless, it is clear that field teams want to view information related to schedule, quality and planning processes. Tezel et al. (2016a) showed that implementing Visual Boards on highway construction sites helped in mapping and preventing problems, brought greater visibility to planning and improved the coordination and harmonization of work teams.

METHOD

The methodology adopted in this study was Design Science Research (DSR), a method in which the strategy helps in the search for solutions in the field of innovation and continuous improvement by using the research strategy (Carneiro et al., 2019). This research model seeks to develop valid artifacts and reliable knowledge for problem solving (Van Aken, 2004), reiterating that its use must be developed based on the usefulness it will have for the organization and literature, by developing and applying theoretical knowledge (Monteiro, 2015; Järvinen, 2007; Lukka, 2003). The artifact developed was the Collaborative Method of Logistics Planning for sizing the quantity of equipment needed over a period of 6 weeks, linked to a Visual Framework, for highway construction projects.

The method was applied in a pilot study of a highway construction project executed by Company A. Company A operates in the heavy construction sector, offering infrastructure solutions, and has over 1200 employees in its workforce. Company A did not have a specific structured planning method, at the long-term level there was a Gantt-based planning software due to the need established in the contract with the highway concessionaire, the lookahead planning didn´t exist and at the short-term level there was formal planning but without collaboration between team leaders. However, the isolated tools was not sufficient to meet the complexity presented in this project and did not allow the visualization of possible conflicts between different services in the same locations.

The company was starting a Lean transformation process, and this project was chosen as a pilot due to its size and complexity, as the project was already partially executed when Company A entered the project. The construction project, still under construction, is located in Brazil, in the state of Santa Catarina, and has 37 km of extension. The authors of this work were part of the Lean implementation nucleus, consisting of external consultants and collaborators from Company A. The implementation of Lean Construction within the pilot study started in May 2022 with the application of the Last Planner System (LPS).

The steps followed by the research were: (i) identification of the problem after the implementation of the LPS; (ii) mapping Company A's internal systems for adjusting resources; (iii) development and application of the method; (iv) review of the method based on data analysis; (v) assessment of the methodology developed through employee survey and result analysis. The survey was focused on understanding the evaluation of the employees regarding ease of use and usefulness.

The Logistics Planning method was developed iteratively, taking inspiration from the playful approach of some logistic simulation software such as AnyLogic. The parameters and resources sizing calculation were based on Mattos (2019). Table 1 summarizes the main sources of observation used to refine the artifact and collect data for analysis.

Table 1: Main sources of evidence.

Case Study	Highway Construction Project
Duration	6 months
Number of meetings	12 meetings (estimated total of 24 hours)
Participant observation in planning meeting	Bi-weekly Logistics Planning meetings and daily huddles
Role of the observer	Initially led meetings during routine implementation. Then transitioned to a spectator providing insights and improvement suggestions for meeting management
Direct observations	Informal conversations and observations during the daily huddles
Document Analysis	Schedule, daily huddles, weekly plans, and the materials factory, internal processes for hiring and mobilizing equipment and purchase of material
Employee Survey	10 Collaborators (field managers, engineers, project director, and contract manager)

The project involves a two-lane highway with flexible pavement and five layers. Excavation is done first, followed by rock fill and subgrade layers (25 cm each) locked with fine material. Sub-base layer (25 cm) follows with Macadam and fine material. Then the Single-Sized Gravel (SSG) base layer (15 cm) and the hot mix asphalt (HMA) pavement layer (3 parts) are added. Understanding each layer is important for specific equipment and cycle times, affecting logistics planning.

METHODOLOGY DEVELOPMENT AND INITIAL RESULTS

PROJECT DIAGNOSTIC ASSESSMENT

The project started with the introduction of the LPS and its management tools, as requested by Company A. A Master Plan was developed using the Time-Location planning technique and daily Check in-out meetings were established. Using these daily routines, relevant data and key performance indicators (KPIs) were collected to detect issues in the field. The analysis revealed that equipment-related interferences from field teams accounted for 43% of all interferences, with much of it stemming from inadequate supply to the service fronts. Further on-site inspections were carried out to determine the true nature of the problems reported by the field teams.

A notable aspect of the project undertaken with Company A is that two other companies had previously carried out separate sections of the highway. This added complexity to the planning process, as the activities were not performed in a linear manner and internal logistics were hampered by the extended travel required to cover the scattered activities throughout the construction site.

During the workflow analysis in the service fronts, a clear connection between value aggregation and equipment resources was identified. Figure 1 showcases one of these observations carried out in the Macadam work front in August 2022. During a 1 hour and 30 minute observation period, it was observed that the tractor remained idle for 52 minutes, accounting for 58% of the total time. This idle time is represented in red in Figure 1, while the green section represents the time when the equipment was active. This revealed that the equipment quickly returned to inactivity after a period of truck unloading. As a result, the number of dump trucks was adjusted to increase the delivery frequency of materials and meet the daily production target set in the Master Plan. The findings align with those in the literature. Haronian and Sacks (2020) carried out three studies to calculate value aggregation in earthwork fronts and found that the percentage ranged from 36% to 58% of the total work time.

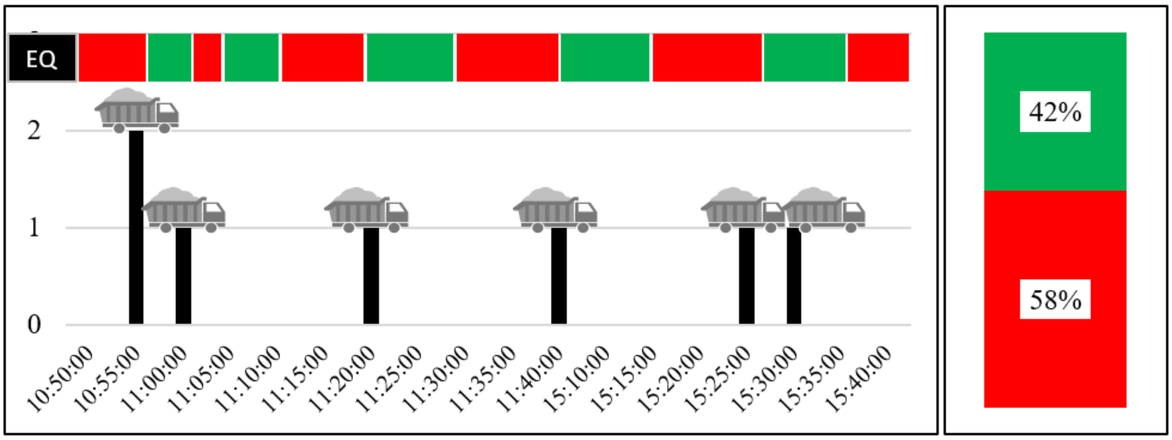

Figure 1: Field observation based on chronoanalysis carried out on the macadam front in August 2022.

Additionally, initial interviews were conducted and it was identified that field staff had difficulty visualizing medium-term constrains when presented with work plans outlined in the standard LPS models. This highlights the shortage of the medium-term model, as field employees struggled to map and size equipment for the sections that needed to be produced. Given this information and the imbalance of field resources, it became necessary to develop a routine that could dimension the necessary resources in advance for the project's execution, while also having the action plan for the coming weeks represented in visual charts alongside the project map.

Given the demand for the improvement of LPS routines for field teams, a complement to the classic framework by Ballard (1994) was proposed, as shown in Figure 2, combining the Look Ahead Planning routine with Logistics Planning. To this end, a method was created for sizing equipment needs according to what was planned in the Master Planning, using the expected productivity and cycle times of each equipment, in order to better visualize equipment-related restrictions.

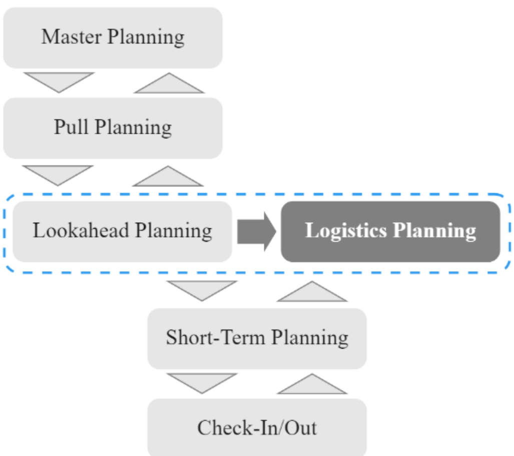

Figure 2: Proposed Logistics Planning and LPS Framework, adapted from Ballard (1994).

Logistics Planning is positioned alongside the Lookahead Planning step due to their similarities. Lookahead Planning seeks to visualize a production horizon, based on updates and adjustments to the Master Planning, and through the mapping and removal of constraints, allocate only activities that are cleared for execution in the upcoming weeks (Ballard, 1997).

To determine the study horizon in this routine, the average time for driver and equipment mobilization was checked with the human resources and equipment departments within the company. During the study, it was found that the average time between the request and the entry of employees with the equipment took, on average, 4 weeks. Hence, the method presented here takes place within a 2-week interval, with a planning horizon of 6 weeks, in order to have a reasonable hiring time when an eventual need is identified.

METHODOLOGY DEVELOPMENT

After conducting this diagnosis with the work teams, the need to hold a Logistics Planning meeting on the construction site to calculate the quantity of equipment was identified. A 6-step model was then developed for conducting Logistics Planning in highway construction projects.

Step 1: Scope Analysis

In this first step, it is necessary to have the Master Plan developed, with a clear action plan, as well as to have the productivity of the equipment of each service fronts, as shown in Figure 3a. In the Company A scenario, six main services are identified: Excavation, Rock Fill (or Land Fill), FEL (Final Earthwork Layer), Macadam, SSG (Single-Sized Gravel), and HMA (Hot Mix Asphalt). For each of them, there are productivity rates planned to meet the long-term planning, along with the equipment's own productivity. With this information, it is possible to analyze the production volumes for each of the lots and the deadlines for completing each activity in the location where it should be executed.

Step 2: Sequencing of Fronts

After completion of Step 1, the action plan is reviewed and defined with the field team, as well as the sequencing of the service fronts. This step aims to map out the ideal workflow for executing the work, considering the priority production batches and also the contractual milestones imposed by the client. As shown in Figure 3b, the fronts that will be worked on over the next 6 weeks are placed in the Visual Board. Different colors were used for each service in order to visualize the workflow over the weeks. It is also important to consider the interdependence between activities, so that all can be completed in an adequate manner.

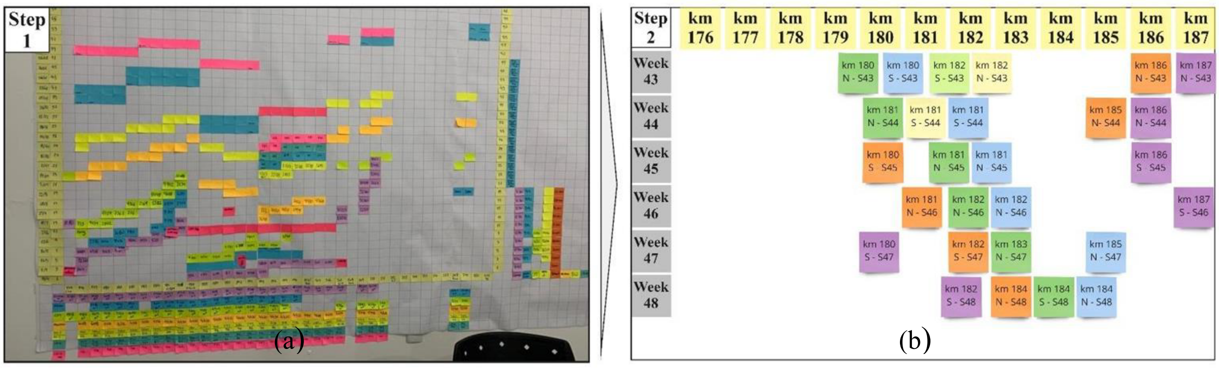

Figure 3: (a) Step 1: Master Plan defined; (b) Step 2: Visual Board with 6-week planned work fronts.

Step 3: Supply Logistics

In this step, the feasibility study and analysis of material extraction sites is carried out in order to attend the construction production and visualize the material supply routes and note the necessary distance for material transportation. The Visual Table indicates where the material pickup (Storage – ST) and deposit locations (Land Fills – LD) are, as shown in Figure 4a.

Step 4: Supply Cycles

With data already analyzed in the field, such as cycle time (Figure 4a), material loading and unloading, as well as the information on location, execution deadline, transportation distance, and heavy machinery productivity, a calculation is made of the number of dump trucks required, as well as the number of trips needed by each truck throughout the day, to meet the established goals. The information on the compliance with the plan is then collected in daily huddles, in order to have an agile response and schedule corrections within the same week.

Step 5: Resource Sizing

With the drawn plan, it is possible to balance the best workflow, respecting large mobilizations and demobilizations of trucks from week to week. Thus, the aim is to arrive at a plan that is more consistent with the reality of the work. The logistics planning is updated every 2 weeks, i.e., there is always a 4-week protection for the planned horizon, which, as mentioned earlier, is sufficient time to mobilize equipment and drivers within the company. With the work fronts and locations of material removal and deposit defined, as well as with the number of dump trucks established, it is possible to design the truck routes on the Visual Board, as shown in Figure 4a, thus starting Step 6.

Step 6: Constraint Analysis

As part of the Lookahead Planning routine, in this phase, employees are encouraged to map out any constraints that may hinder the execution of the proposed plan. With the Logistics Planning Visual Board positioned below the job site map, employees found it easier to map production risks and see attention points that could impact labour productivity in each service front. From the mapping of the restriction, proactive actions can be taken to mitigate or even eliminate it before it becomes an interference and, as a consequence, impacts the productivity of the work front. For each mapped constraint, actions and responsibilities are listed on another Visual Board, to eliminate them and thus release the activity for execution. To protect production, these actions are transferred to a spreadsheet by the Planning team and sent to each of the responsible service front parties. As the actions are completed, they feed the Constraint Removal Index (CRI), as shown in Figure 4b.

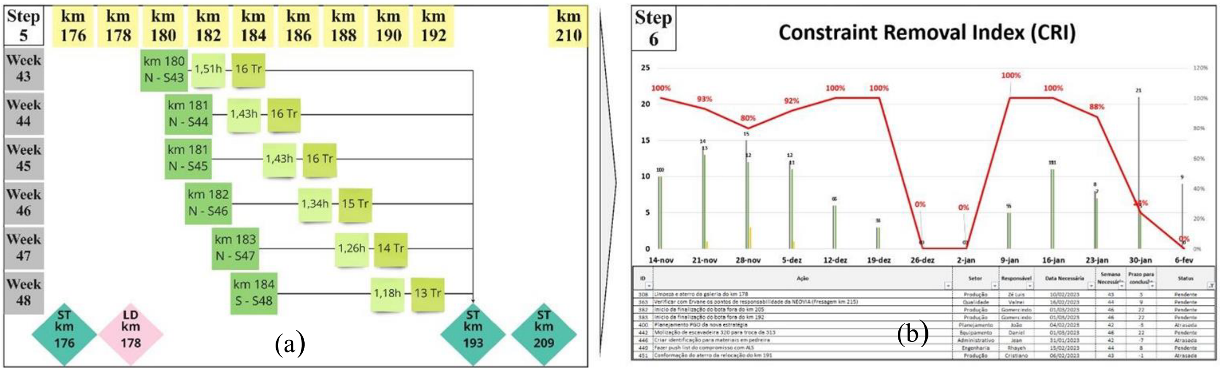

Figure 4: (a) Step 3 to 5: (3) Locations and routes of deposit and withdrawal of material mapped; (4) calculation of the cycle time; (5) Sizing and balancing resources; (b) Step 6: Control of removal of restrictions based on visualizing obstacles to productivity.

As these 6 steps were developed, it was possible to observe a greater level of worker and field team engagement in adhering to the long-term planning, considering the increase in PPC, as shown in Figure 7a, and the productivity in the field, Figure 7b. Furthermore, with the implementation of the Logistics Planning Visual Method, workers were observed to have developed a higher level of responsibility regarding the elimination of the mapped restrictions. Beyond participation in the meetings, workers would take photos of the visual board, presented in Figure 5 in order to meet established goals. This team engagement confirms what Ballard and Tommelein (2021) bring in their LPS benchmarking work. The Lookahead meetings should be collaborative, involve all the responsible parties from the service fronts, including the decision makers and on-site workers who can provide the necessary information for the meeting to proceed. Only in this way is it possible to create a functional activity sequencing plan with flows and transformations.

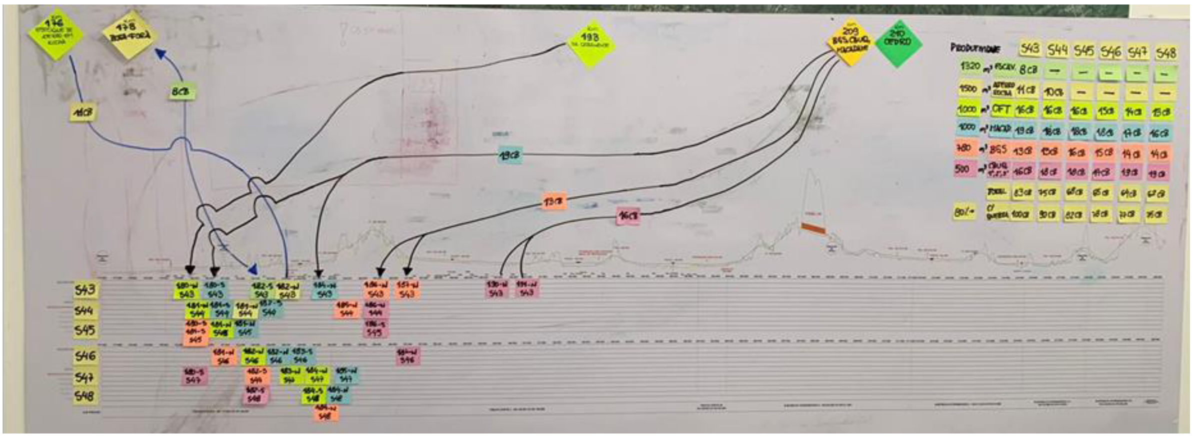

Figure 5: Routine of Logistics Planning and Visual Table of sizing trucks and routes

INITIAL RESULTS

After the implementation of the 6-step Logistics Planning method, an improvement could be noted in the primary indicators consulted, when compared to the months of June, before the beginning of the Logistics Planning meetings, and November, after the beginning of the Logistics Planning meetings. The total hours of impact correspond to the hours that services remained stopped, whether due to lack of material, equipment, project, or other factors. Hours related to equipment refer specifically to those hours that services remained stopped due to a lack of equipment. Figure 6 shows that the total number of hours of impact in productivity during the Check in-out meetings decreased from 881 hours in June to 278 hours in November, which represents a 68% decrease in total hours. Similarly, a decrease in the hours of impact related to equipment was observed, from 43% (374 h/881h) in June to 29% (81h/278h) in November.

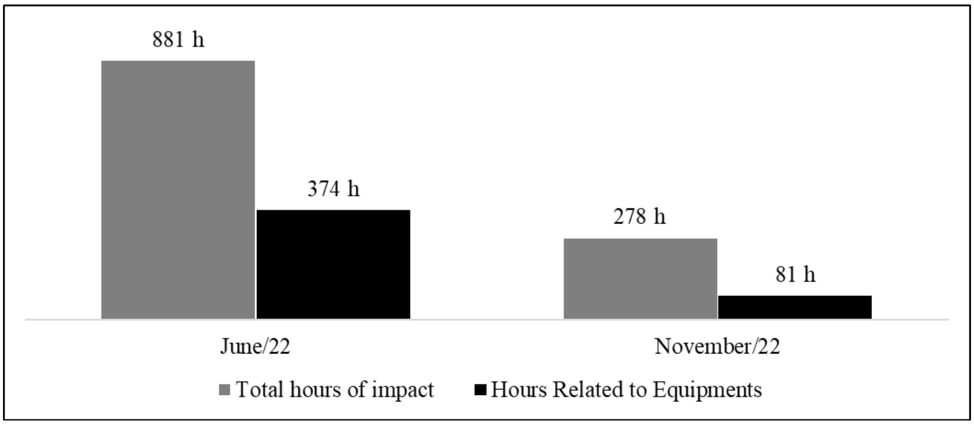

Figure 6: Hours of impact in productivity, total and equipment-related.

There was also an improvement in the PPC indicators, as shown in Figure 7a. The PPC indicator showed continuous growth since June, from 20% to 52% at the end of the collection in November. This percentage is due, among other factors, to the complexity of the section, as mentioned during the implementation of the LPS, and due to the recurrent rains in the region during that period consisting of rain on 41% of the days.

The data found is corroborated by Tezel et al. (2016a), who, in two road projects, identified an increase in PPC after the implementation of visual management on the construction site. In the first, PPC increased from 60% to 85%, while the second had an average PPC of 76%. Drysdale (2013) also achieved similar improvement values, rising from 59% to 85% in Percentage of Plans Concluded.

Figure 7b shows an improvement in the indicators of labour productivity. This indicator was used to identify whether the Logistics Method helped the team, resulting in an increase in production from the Sub-grade, Sub-base, and Pavement Base fronts. Thus, the calculation used to verify this increase was the ratio between the monthly volume produced and the number of hours worked. For the Sub-grade front, there was a 64% increase in productivity between June and November, while the Sub-base and Base front saw a 7-fold increase in productivity.

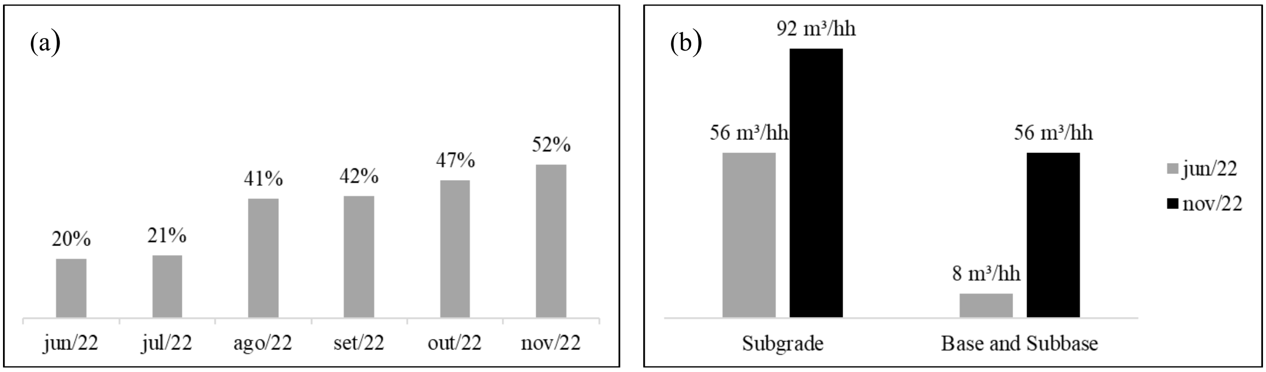

Figure 7: (a) Percentage of Plans Concluded (PPC) during the development of the Project: (b) Increase in Productivity of the service fronts before and after starting the Logistics Planning meetings.

In order to evaluate the usefulness and effectiveness of the proposed method in mapping constraints, and to separate the normal learning effect of teams, a survey with ten collaborators were done, including field managers, engineers, project director, and contract manager. Their responses, tabulated in Table 2, indicate a widespread approval of the method. While three out of the ten interviewees reported challenges in applying the method, all of them expressed the inclination to recommend it for future projects.

Table 2: Main sources of evidence.

N	Questions about the Logistics planning method	Strongly Agree	Agree	Disagree	Strongly Disagree
1.	Do you use the method for highway construction in your company?	9	1	-	-
2.	Is the method used by the company efficient?	8	2	-	-
3.	The method used by the company has improved the mapping and analysis of constraints?	9	1	-	-
4.	The method used by the company has improved the perception of resource sizing?	9	1	-	-

5.	The method used by the company has improved the visualization of where to deploy resources?	8	2	-	-
6.	Do you consider the logistic planning tool used by the company easy to apply?	7	3	-	-
7.	Considering usefulness and ease of use, do you approve of the method used by the company?	9	1	-	-
8.	Would you recommend the use of this method for future projects?	10	-	-	-

CONCLUSIONS

This study presents a new Logistics Planning methodology implemented in a Highway project between May and December 2022. The objective was to analyze the feasibility of using a logistic planning method with the aid of a Visual Board, combined with the Last Planner System.

The methodology employed is well-suited for LPS and is complementary to Lookahead Planning, given their similarities: (i) definition of the production batch sequencing; (ii) mapping and removal of production constraints; and (iii) the need to hold collaborative meetings. Six steps were developed to increase the lookahead planning, consisting of: 1. Scope Analysis; 2. Sequencing of Fronts; 3. Supply Logistics; 4. Supply Cycle; 5. Resource Sizing and 6. Constraint Analysis.

After the implementation of the methodology, a decrease in the number of impact hours (total and equipment-related), was observed. Additionally, there was an improvement in the PPC and productivity indicators of the service fronts. The results are corroborated by the literature (Tezel et al. 2016a; Drysdale 2013). Furthermore, the more visual and collaborative format of the meetings helped in the engagement of the field teams, who took photos of the developed visual board for on-site use.

Therefore, it can be concluded that the possibility of using Visual Management, combined with logistics planning, stimulates the engagement of the operation's employees around the construction schedule, increasing the accuracy of the Master Plan, confirming the hypothesis proposed.

An interview was conducted to perform a cross-analysis between the users' perception regarding the usefulness and effectiveness of the method. It was possible to perceive that the method was widely approved of, although some interviewees found it challenging to implement. Nonetheless, all interviewees expressed their willingness to recommend the method for future projects.

Despite finding improvements with qualitative and quantitative data, the implementation of Lean in highway construction projects must take into consideration the need to actively involve field collaborators in routines that facilitate the visualization of restrictions, in a simple manner that is easily understood. Companies need to go beyond simple implementation and actually incorporate supply chain and equipment routines into their projects, making strategic decisions aimed at increasing efficiency in the sector.

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LEAN CONSTRUCTION THROUGH WASTE REGISTER METHOD: A CASE STUDIES PROJECT IN INDONESIA

Rina Asri Aisyah[1], Kevin Gunawan[2], and Abdhy Gazali[3]

ABSTRACT

Waste in construction projects is a significant research topic globally, including in Indonesia. The lean construction concept identifies any waste as a non-value added. Different waste management techniques categorize waste as either physical or non-physical. Based on literatures explain that most of project construction is bad on waste registration. The paper focuses on implementing lean construction for physical construction waste. Furthermore, this article presents Indonesian case studies to illustrate the impact of lean construction on building projects.

The study analyses waste management impacts across three periods of time. Lean waste management provides an early warning evaluation in the short term that are used as an indicator, so the project can evaluate and follow up as an effort to reduce waste, which in this study shows a reduction of waste from 2.1% to 1.7%. Addressing common waste in the medium-term increases project productivity by 50% and improves cost and duration efficiency. It reduces many possible wastages due to defects, overproduction, non-utilized talent, inventory, transportation, motion, waiting, and extra processing (DOWNTIME). Sustainable waste reduction practices can become a productivity standard in the long term by continuously improving the cycle of writing, categorizing, analysing, and writing for each job.

KEYWORDS

Lean construction, waste, productivity, value, continuous improvement

INTRODUCTION

The complexity of project construction has been considered based on production management, that must be designed, scheduled, produced, and presented in a timely manner. It is therefore characterised by delays and has often experienced cost and time overruns. (Vidhate, Tejas et al., 2018). A significant amount of construction waste has depleted the industry's total performance and production, and thoughtful action should be taken to address the undergoing state of affairs. According to the Lean Construction Institute (2004), the construction industry accounts for approximately 57 per cent of productive time lost (Ansah, Richard et al., 2016).

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Waste in the construction industry not only a problem for the construction industry, it also has an impact on the economy of a country as a whole. The elimination of material and time wastage would improve the performance of the project, increase value for individual clients as well as providing a positive impact on the domestic economy (Polat & Ballard, 2004).

In recent years, many research studies around the world have focused on waste from the construction industry. Construction waste research suggests that a construction project produces large amounts of waste (Esin & Cosgun, 2007; Wanga et al., 2010). A variety of methods have been used over the past decades to reduce construction waste as well as its impacts. One of the most effective techniques is the adoption of a lean strategy in the construction industry. Lean construction is also the result of an innovative approach to production management to address the complexity of project construction. The fundamental idea of Lean Thinking is to cut waste in order to increase performance. Project managers generally take the view that "waste" is tangible construction waste. However, there is observable waste in the construction process, often referred to as "non-adding activities" in the lean construction method. (Hosseini, et al., 2012).

Construction management community efforts to understand waste are relatively low in comparison with other topics. Many research on waste has tended to focus on effects rather than avoidable root causes (Viana et al., 2012). Lack of integration of waste management into planning and control procedures and requirement not only to confirm but also to observe the efficiency of building processes (Formoso et al.,1999). In addition, it is necessary to enhance the model in order to obtain a precise understanding of the areas of lean construction principles and techniques where Indonesian contractors are deficient and require enhancement and promotion (Abduh et al, 2005).

Usually, project managers define waste as physical construction waste, which mostly includes material losses (Koskela, 1992). However, lean thinking focuses primarily on waste produced during a construction process, which can be separated into two main types: waste arising from the nature of the process and waste arising from work without added value (this group includes wait times, value-neutral activities and transportation of materials). It should be noted that not all waste related to the construction process can be attributed to the process itself or to non-value-added activities. But since only one class predominates, it will be assigned to each subdivision (Hosseini, et al., 2012).

Productivity and waste metrics can complement one another. There are similar fundamental reasons for waste and production research: to learn further information on the current situation in order to make improvements. Consequently, it can be useful to look at waste and productivity levels (Forsberg & Saukkoriipi, 2007). Based on literatures explain that most of project construction is bad on waste registration. This because of project complexity that effect the activity of collect and analysis waste never successful. So that, waste in the project already known large in the end of period time projects.

This research focus on the implementation of the lean construction principle in waste management, especially for physical construction wastes. We apply the Pareto item principle to the waste register method for materials such as concrete and steel works. An actual experiment is required for testing and assessing waste mitigation due to lean construction principles implementation in construction processes. The study therefore focused on strengthening operations in building projects in Indonesia.

WASTE MANAGEMENT

TYPE OF WASTE

The seven wastes of lean production that are often found are as follows: 1. Transport: unnecessary and ineffective flow of information; 2. Inventory: information waiting to be processed; 3. Motion: editing, verifying or creating inquiries; 4. Waiting: awaiting information; 5. Overprocessing: verifying, reprocessing, repeat applications, new procedural codes; 6. Overproduction: multiple bills, duplicate files, minor debt lawsuit; 7. Defects: complaints, corrupt or mis-coded data, recording and transcription errors, unauthorized procedures (Koskela et al, 2013). Several candidates were proposed for the eighth type of waste (Macomber & Howell, 2004) identify several of them, which can be categorized as: failing to use people's talents, skills and abilities; wasting information; wasting behaviours; and wasting good ideas. Waste comes in eight different forms in lean manufacturing. The seven well-known wastes focus on the production process, but the eighth has a direct impact on management's ability to employ staff (Brito et al., 2019). In this paper the eight wastes are defined by DOWNTIME (Defect, Overproduction, Waiting, Non-Utilizing Employee, Transportation, Inventory, Motion and Extra-Processing).

Waste identification will undoubtedly impact the results of the projects implemented and support sustainable development. The main pillars of the sustainable concept itself are people, planet, & profit (Crane & Matten, 2004), or the triple bottom line. Therefore, it is crucial to consider the needs of people or social aspects, the planet or environmental factors, and profit or economic aspects, especially in lean construction implementation. The waste will undoubtedly directly impact the environment, but not only that, because construction waste indeed involves collaboration on the lean principle of "respect for people," which supports the social aspects of sustainable development. In the end, the expected value in identifying this waste is to reduce costs due to waste that occurs and support profit or economic aspects to realize sustainable development.

WASTE IDENTIFICATION & REGISTRATION

As a result, we can anticipate the discovery of waste chains during the review of process waste. These are a range of causes and consequences in which one waste causes another. (Koskela, Bolviken, & Rooke, 2013). For example, one of the usual construction industry problems is the delivery process of the materials (Thomas et al., 2022). Equipment and workers are often held in abeyance because delays occur in the supply of materials and the finishing of preliminary work. This issue reduces productivity and prolongs the duration of the project (Tommelein, 1998).

However, responding to downstream demand too quickly results in a waste of inventory and may result in additional expenditures. Another fundamental lean manufacturing strategy known as "pulling" to ensures just-in-time synchronization between upstream and downstream processes. It is based on the notion that the upstream should not deliver a product or service until the downstream request it (Womack & Jones, 1996). Macomber & Howell (2004) identify other waste: failure to use people’s talents, skill and capabilities; information waste; behavioural waste; and wasting good ideas. This type of waste was categorized non utilize employee due to the practice of improvising to compensate for inappropriate upstream operations is particularly worrying as a major waste in construction (Koskela, Bolviken, & Rooke, 2013). If we compile this type of waste, there is eight waste taxonomy, defect (making defective products), overproduction, waiting (time on hand), non-utilize employe, transportation, inventory (stock on hand), motion (movement), and extra processing (over processing).

RESEARCH METHOD

This study uses trend and regression analysis to conduct studies related to the relationship between the parameters recorded in the waste register that occur in the project with other parameters in the production planning that is being carried out. The waste register in this study records two major elements: bodily waste and productivity. These two major elements are then recorded and analysed in a monthly basis according to the data realization and evaluation that can be carried out in production planning in the field, which in this case is carried out using the Last Planner System (LPS) method. Project records between the material that is recognized by the owner and the material that we bring in on a monthly basis, in order to get the trend from the pattern of waste that occur.

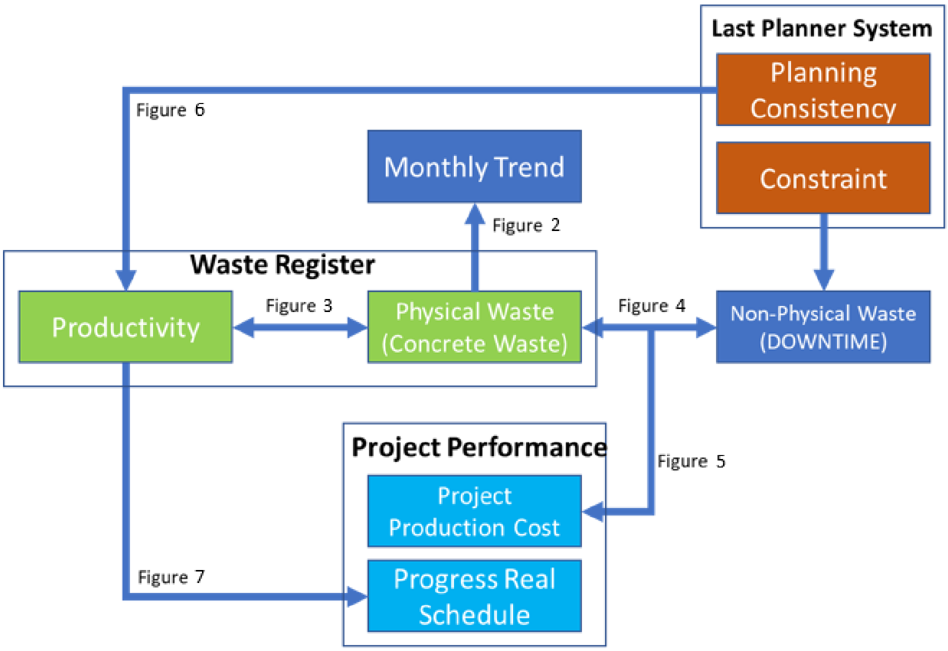

Figure 1: Research Method

The physical waste registration carried out in this study is done by examining the physical parameters that can be measured, namely concrete waste. This is done so that these parameters become a comparison with other performance parameters, which will be correlated because of using the waste register. The concrete material was chosen because it is one of the dominant (pareto) materials implemented in the work items on the project in this study.

Furthermore, an analysis is also carried out related to non-physical waste obtained from constraints that occur in the production planning stage using the Last Planner System (LPS). This constraint is then converted related to the impact of waste generated in the realm of DOWNTIME (defect, overproduction, waiting, non-utilize employee, transportation, inventory, motion, and extra-processing). In this study, the LPS result is used to see the effect of constraint analysis which then related to the concrete waste materials to be measured. This method applies so that the root cause analysis carried out in the LPS stage could become one of the tools that help to discuss the result of waste register that filled in.

WASTE REGISTER METHODOLOGY: IDENTIFY WASTE & PRODUCTIVITY

The waste register is a tool to identify patterns that occur in projects. This pattern is a collection of data that is recorded every month by the project team. The recorded data is a comparison of material that is recognized with what the project team has worked on. recording every month, allows us to see the pattern of productivity that occurs. Productivity is below standard, there must be a waste factor that needs to be evaluated. This is where we can find the direct impact of the waste that occurs with the productivity of a job. We record this waste (physical waste and other downtime waste) per month, the monthly data will be used as an evaluation for the next month as long as the work is still ongoing. The results of the evaluation serve as an early warning if the waste that occurs interferes with the target that has become a joint agreement, both concerning cost and time. The data per month can also be a trend which we can analyse to find the patterns, which makes it possible to find the characteristics of waste based on the type of building (high risk building, hospital, airport, building revitalization."

With respects to materials, equipment and labour, and productivity parameters, we used to determine waste register as a method to require that the objectives of this research suggest various goals in the waste register over time. In the short term, the waste register provides an early warning evaluation of budget costs according to budget waste, potential waste, actual waste, and productivity. In the middle term, mitigating common waste significantly increases productivity as well as project efficiency related to cost and project duration. It reduces many possible wastages due to defects, overproduction, non-utilized talent, inventory, transportation, motion, waiting, and extra processing (DOWNTIME). In the long term, sustainable conduct of waste mitigation can become a productivity standard by iterating the cycle of writing, classifying, analysing, and writing for each work. In this waste register, the parameters of the physical waste that are recorded are concrete waste materials. The unit used in this study is the unit that applies in Indonesia where concrete waste is defined as a percentage (%) and concrete work productivity is defined as m3/OH where this unit is equal to 1 m^3 of concrete produced by one person in one day (m3/man). -days)

CASE STUDY: BUILDING PROJECTS IN INDONESIA

This study is a case study from a building project that recorded waste and productivity on the waste register tools and implemented the Last Planner System method in controlling production on the project. The following is a project profile that is the focus of this research.

Table 1: Building Project Study Case in Indonesia

Project Name	Project Value (before tax)	Project Type	Location	Duration	Contract Types
A	11.862 €	Public	West Java	21 months	Regular; Unit Price
B	60.585 €	Private	Central Java	21 months	Regular; Unit Price
C	41.363 €	Private	Jakarta	24 months	Design Build; Lump-Sum
D	8.376 €	Public	Jakarta	10 months	Design Build; Lump-Sum
E	21.189 €	Public	Bali	17 months	Design Build; Lump-Sum

ANALYSIS

WASTE TRENDS

This waste trend is an output trend resulting from the monitoring of several projects in Indonesia carried out through the waste register method as a mention earlier in the waste registry methodology. This can be concluded through the time parameter that the more waste is recorded and monitored in a project, the quantity of waste decreases every month (confidence in a trend with an R-value or confidence level of 0.647).

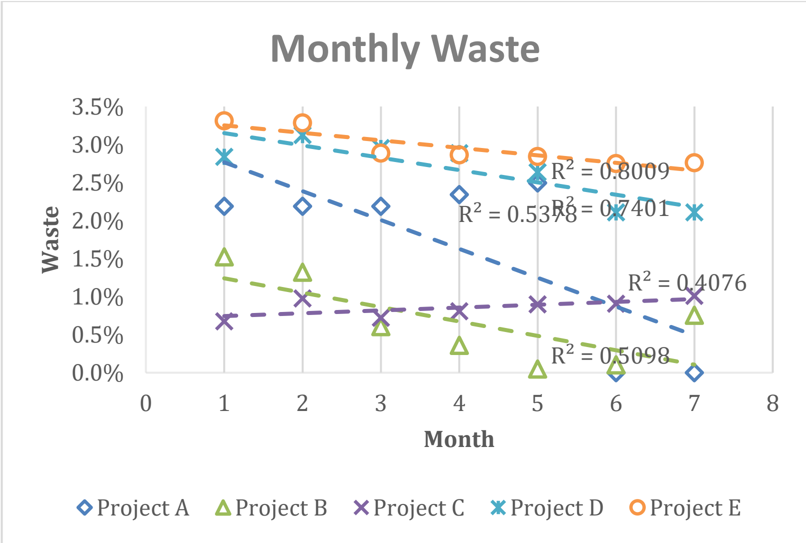

Figure 2: Comparison Between Waste & Time (Month)

The waste above is physical waste recorded in real terms from the Pareto elements in construction work, namely concrete waste. Based on the graphic in Figure 2, we can see that each project has the same linear pattern, then various trends refer to their activity according to waste monitoring in months. The high R-value means project has been considering doing waste monitoring each month; the highest order is from Project E 0.8009, Project D 0.741, Project A 0.5378, Project B 0.509, then Project C 0.4076.

The data show that Project C gets a positive gradient, meaning their waste is increasing every month. The first waste is already low; therefore, so the following record maintains the low trend baseline. Meanwhile, in the end, waste will increase. Therefore, even though the waste trend of Project C increases, the actual waste is still low. Based on the data in Figure 2, we can see that in the first month the average waste rate was 2.1%. This value shows the excess volume of concrete that occurs from the required initial volume. However, in the 7^{th} month, the measured waste decreased to 1.7%. This indicates that the recording of waste has affected.

Impact of Controlling Waste on Productivity

The waste register records the productivity of Pareto items production to the amount of workforce of each work. This productivity measured in this research is the amount of concrete volume compared to the amount of workforce. The purpose of this parameter is to see how controlling waste could impact productivity results.

The data in Figure 3 shows that the most controlled waste will be the lowest; refer to evidence obtained previously. Therefore, the productivity of concrete works in all projects also will be high. The graphic also shows the trends described by a negative gradient, although this is still a low regression value. Meanwhile, the trends may be explained by the fact that waste monitoring will prevent productivity improvements in the project. The result indicates that the projects have a confident correlation within the average value of regression is 0.350 (moderate). The graph shows an average increase of approximately 50% in the productivity of concrete work based on a decrease in waste from 2.1% to 1.7%. This means that the project could control its waste management and have an opportunity to increase productivity.

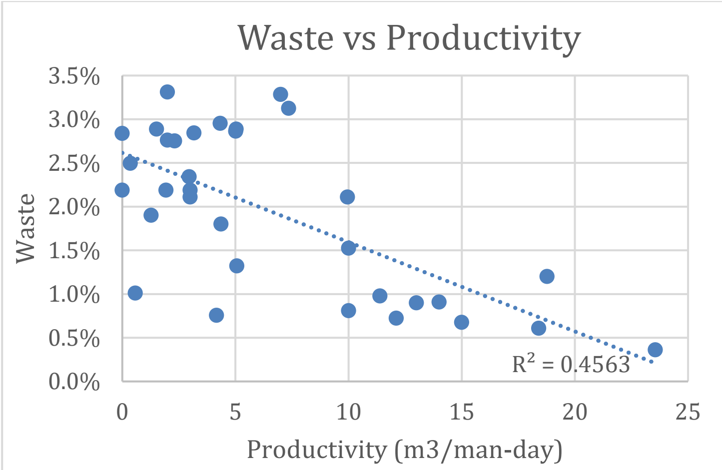

Figure 3: Comparison Between Waste & Productivity

In addition, the other tool of lean construction, the Last Planner System (LPS), already recorded the waste in terms of constraints that happen in the project. The constraint data which doesn't closed then analysed to determine a non-physical waste that we called DOWNTIME (defect, overproduction, waiting, non-utilizing people, transportation, inventory, motion, and extra-processing). This DOWNTIME score is obtained from the constraints that occur in the LPS implementation, as shown in table 2 below:

Table 2: DOWNTIME Score from LPS Constraint

CONSTRAINT / VARIANCE		D	O	W	N	T	I	M	E
1. Procurement of Materials & Equipment	INTERNAL FACTOR	1		1			1		
2. Subcontractor / Foreman (Contract)		1		1					
3. Procurement of Light Equipment / Auxiliary Equipment			1	1					
4. Payment to Vendors				1	1				
5. Design Decisions	OWNER FACTOR	1		1					1
6. Approval Shop Drawing / Method		1		1					
7. Material Approval				1			1		
8. Owner's Request		1	1						1
9. Land Handover / IMB				1		1			
10. Payment from Owner				1			1		
11. Limited Resource Subcontractor / Foreman	EXTERNAL FACTOR			1	1			1	
12. Limited Supply of Materials				1		1	1		
13. Time Limitation & Work Operations			1					1	1
14. Local Vendors Not Qualified		1			1				
15. Previous Work Not Completed		1		1					1
16. Weather / Natural Disasters				1					1

Figure 4 shows the correlation between the physical waste and non-physical waste. The graphic explains that if non-physical waste (DOWNTIME), there is a chance that physical waste will increase. One of the possible things that we can adjust is that this happens because the project cannot maintain physical waste, mostly defects and the overproduction type of waste.

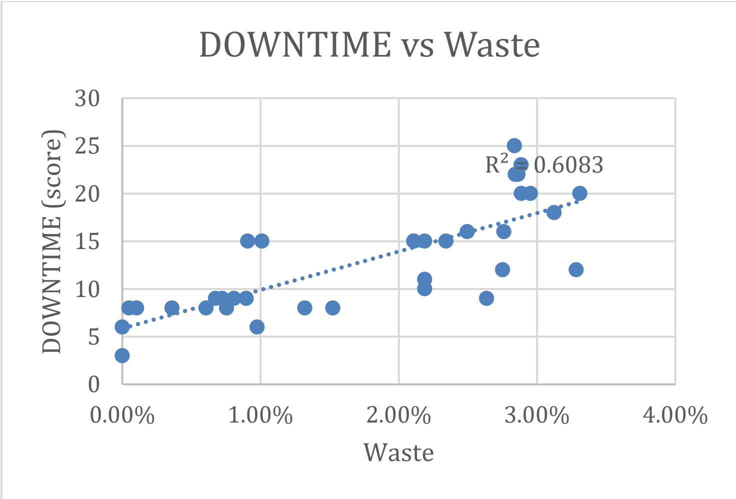

Figure 4: Correlation Between Waste & Waste DOWTIME

Waste & Project Production Cost

Ultimately, this waste monitoring will impact the project's performance. One of the indicators is cost parameters. Recording of waste which is done through the waste register form indirectly affects the cost performance parameters of the project under review. The cost parameters which are compared in the present study are monthly production costs which include direct costs and indirect costs which are reported in real terms every month along with the results of recording waste. It is shown by the percentage of the value, which is the amount of cost incurred compared to project cost, which the owner approves.

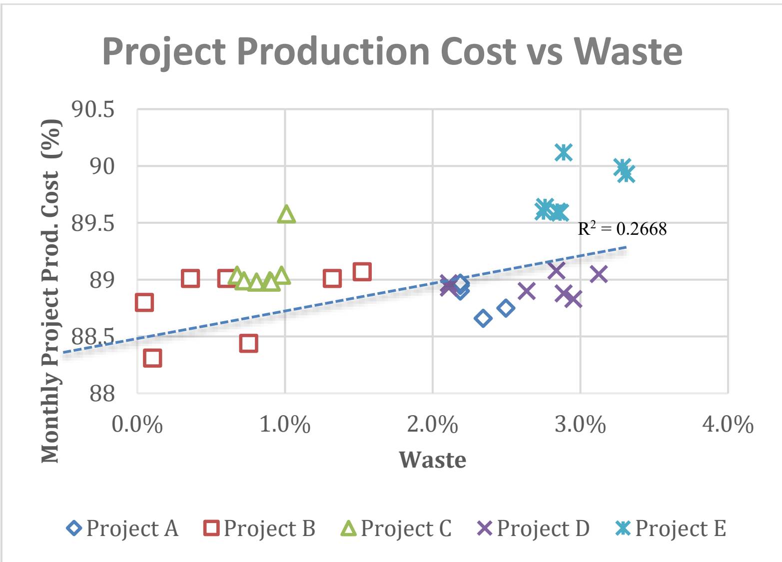

Figure 5: Correlation Project Production Cost vs Waste

The data above (Figure 5.) shows that all the projects have increased waste in the period and that increased production costs will impact on that period. This case, absolutely affected by costs incurred due to waste itself, is Pareto items, so it will impact all cost projects. In addition, if a project could control waste and reduce its value, it would decrease the monthly cost of production. We can see convincing data from the result that when the project can control waste, the cost will decrease with a correlation value of 0.2668.

Planning & Productivity

According to the waste registry method, the productivity value could be compared to the project's ability to plan better using The Last Planner System (LPS). In this case, the well-planned from the previous month will have a high consistency of planning (≥1). At the same time, the project that changes the planning to a lower target plan could be stated as not having good planning (<1). As shown in (Figure 6.), the average concrete productivity is 4.7m^3/person-day, which is considered on the basis of each of the consistent planning results for productivity.

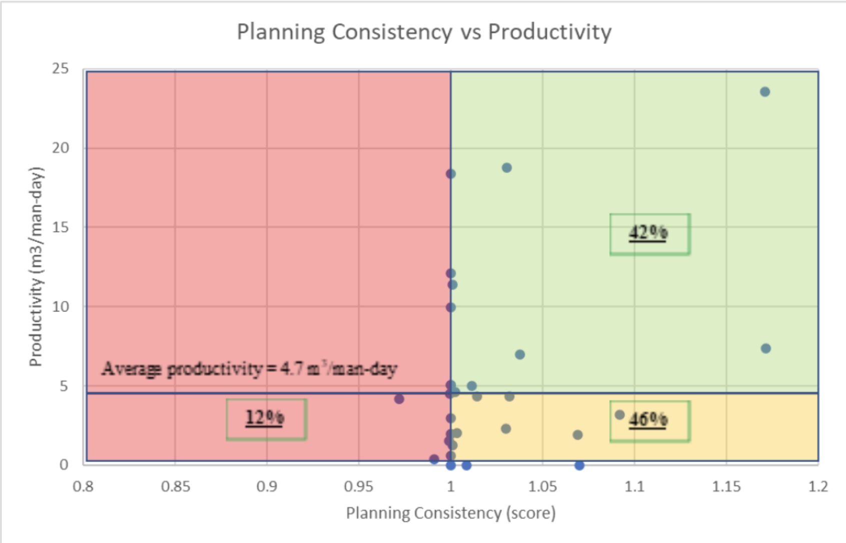

Figure 6: Impact on Planning Consistency and Productivity

The aforementioned data shows that when the consistency of planning when LPS is good (score ≥ 1), productivity is also improving. However, from the quadrant description above, there is still around 46% correlation value between planning consistency and productivity, which is below the average productivity value even though it already has good planning consistency. However, when planning consistency could be better (score <1), there is no doubt that the productivity value will be below average.

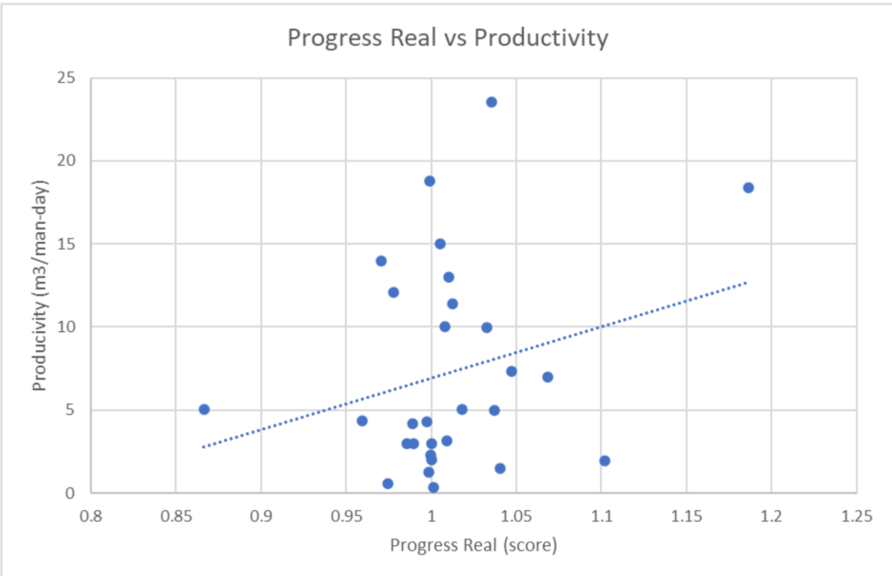

Figure 7: Correlation between Productivity with Progress Score

Ultimately, in line with the above conditions, that high productivity will benefit from a better performance in view of an excellent progress project result with improved productivity. Figure 7 explains that the correlation between productivity monitoring and progress results must be even higher. However, it also shows that the gradient value has a positive trend result. This is because physical waste and controlled productivity are just the dominant types of waste.

CONCLUSIONS AND PERSPECTIVE

The waste register method is a part of lean construction tools in the project for making a better improvement by controlling waste as a routine. Control and monitoring also do the same for the productivity from items of work. We can see from the resulting trend each month that projects with consistent waste recording will better impact the amount of waste in the project. The reason is that there is a control and monitoring process. In the final project, we will show the amount of low waste because we already have an early warning system from the internal team project to control waste. This is indeed affected by better productivity and project costs that can be reduced when controlling and monitoring waste as a routine.

In addition, recording waste project also benefits from seeing the impact of production plan control one of which is the Last Planner System (LPS) or other tools in the project that lead the lean construction concept. However, in the future, we still need to consider non-physical waste, which is being quantified and could be compared to the result based on the time and cost of the project.

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INVESTIGATING EMERGENCE OF ‘NEW TASKS’ IN LAST PLANNER® SYSTEM: SOCIAL NETWORK PERSPECTIVE OF PLANNING BEHAVIOURS

Anukriti Gupta[1] and Ganesh Devkar[2]

ABSTRACT

The Last Planner System (LPS) is a collaborative planning process aimed at ensuring the efficient and timely completion of construction tasks and fostering trust among project participants. Despite its widespread adoption, it has been observed that ‘New Tasks’ that deviate from the original plan often arise in construction projects. This paper investigates the planning behaviours behind the emergence of these New Tasks by examining the social interaction patterns within a construction project.

Three different construction projects with varying degrees of LPS implementation were studied to identify the New Tasks that emerge during the execution process. To understand the planning behaviours related to the New Tasks, the interaction patterns of the individuals involved in the look-ahead planning and the weekly commitment planning were mapped using Social Network Analysis. The findings suggest that a tightly bound network exhibits more cohesiveness and can be associated with effective communication and streamlined information flow which leads to fewer New Tasks. While insufficient coordination and ineffective collaboration can be correlated to emergence of higher number of New Tasks. Look-ahead planning is key in this regard as it incorporates collaboration between all stakeholders into the pull-planning of the tasks.

KEYWORDS

Last Planner® System, lookahead planning, constraint analysis, planning behaviors, social network analysis

INTRODUCTION

Construction projects involve the interaction between unfamiliar groups of people who come together for the project execution and do not always have complementary objectives. Construction planning is seen primarily as a decision-making and scheduling activity with a primary emphasis on identifying deviations from planned activities rather than refining plans for the upcoming week (Laufer & Tucker, 1987). Traditional construction management systems typically involve the creation of comprehensive schedules at the start of projects. However, the inherent uncertainties in construction projects make it difficult to rely solely on deterministic project scheduling methods (Ahuja & Thiruvengadam, 2004). The variability of the highly fragmented construction industry is captured by the Lean philosophy, based on the Toyota

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Production System by Taiichi Ohno. It emphasizes customer value identification, elimination of non-value adding activities, creation of continuous production flow, and continuous improvement (Howell, 1999). Last Planner System (LPS) is one of the most developed lean tools adopted by the construction industry. With the growing complexity of construction projects, the use of LPS is growing in popularity to maintain project activities on schedule by reducing uncertainties in construction operations.

The implementation of the Last Planner System which was developed by Ballard and Howell in the 1990s, enhances work reliability and promotes better coordination among the project participants (Ghosh et al., 2019). LPS works through a series of steps that include the creation of a milestone schedule, a phase schedule, a look-ahead plan, and a weekly work plan involving commitment from the last planners at the site. This approach is based on a pull system as opposed to the traditional planning approach. Despite the systematic and well-planned collaborative efforts in LPS, the actual tasks performed on the job site may sometimes differ from the planned tasks. Tasks that were not previously included in the schedule or were incorrectly scheduled may need to be executed at the site. These are called **'New Tasks'** and arise during the week of the execution.

Hamzeh et al. (2008) first coined the term 'New Tasks' in their PhD dissertation describing them as the most under-reported tasks on a construction project site. These tasks, which do not make it through the look-ahead planning system but appear on the Weekly Work Plans (WWP), are within the project scope but their timelines change for various reasons. Similarly, certain tasks are neither included in the WWPs nor the Look Ahead Plans (LAP) but emerge during the execution week. The inclusion of these 'New Tasks' in the WWP, which were not addressed in the look-ahead planning, greatly impacts the overall workflow and adds additional burden to project planning (Rouhana & Hamzeh, 2016). The reasons for the emergence of these 'New Tasks' have caught the attention of various academicians and practitioners and have been extensively explored (Ballard, 1997; Hamzeh et al., 2012; Hamzeh & Aridi, 2013; Hamzeh et al., 2015; Wesz & Formoso, 2013; Da Alves & Britt, 2011). 'New Tasks' in the weekly work plans of LPS have been reported to arise due to planning behaviours, construction problems and uncertainties (Rouhana & Hamzeh, 2016).

This research paper aims to examine the social interaction patterns, using Social Network Analysis (SNA), in planning behaviours and their impact on the emergence of 'New Tasks' in the Weekly Work Plans of the Last Planner System (LPS). To achieve this, a deep understanding of the planning process, which is influenced by the social interactions and communication patterns among project participants, is necessary. SNA has been used as a prominent tool by researchers to analyse the interactions and relationships between project participants involved in the LPS implementation in a construction project (Herrera et al., 2018; Castillo et al., 2018; Priven & Sacks, 2015; Abbasian-Hosseini et al., 2015; Cisterna et al., 2018). The emergence patterns of 'New Tasks' are investigated in three construction projects located in India that adopted the Last Planner System as their planning method. SNA is conducted to examine the communication and interaction patterns among the project participants involved in the planning process.

The following sections present the literature review, the research methodology, case studies, social network analysis and the conclusion of the study.

LITERATURE REVIEW

LAST PLANNER SYSTEM

The complexities of the fragmented construction industry are addressed by the Lean philosophy, which is based on the principles of the Toyota Production System (TPS) established by Taiichi Ohno for Toyota in Japan (Howell, 1999). Lean construction aims to better meet customer needs by using fewer resources and is a departure from traditional mass production and push-based management practices. It decentralizes organizations, challenges the hierarchical nature of these organizations, and relies on pull-based planning as a fundamental principle.

The Last Planner System (LPS) is one of the most developed lean tools adopted by the construction industry. It incorporates pull planning, in which the Last Planners at the site (foremen/site engineers) are involved in the planning process and are responsible for giving commitments for the work that can be executed within the week after the identification and removal of constraints. The involvement of site personnel in the planning process fosters a culture of trust and commitment amongst the members of the construction project. LPS has five major components: Master scheduling, Phase scheduling, Look-Ahead Planning, Weekly Work Plans and Learning (Ballard & Tommelein, 2016). It is increasingly being used in the construction industry to increase project reliability which leads to better project performance (González et al., 2007).

LOOK-AHEAD PLANNING & NEW TASKS

Look-Ahead Planning is the most important, yet most overlooked aspect of the Last Planner System. Lookahead schedules in construction aim to focus management on future plans and promote present actions towards achieving those goals (Ballard, 1997). It involves the identification of activities to be carried out in the next four to six weeks in a collaborative manner involving all the speciality contractors and consultants. A poor implementation of look-ahead planning in construction projects reduces the reliability of the planning system by creating a large gap between long-term planning (master schedules) and short-term planning (weekly plans) (Da Alves & Britt, 2011). Look-Ahead Planning relies on anticipating the tasks by breaking down the tasks into sub-tasks at the operation level. These tasks are 'made ready' by the identification and removal of constraints six weeks before their actual execution. Hamzeh et al. (2008) conceptualized the phases in construction planning as 'boulders' which are broken down into 'rocks' that represent the processes. These rocks are further broken into 'pebbles' indicating the operations and finally, the steps are represented by 'dust'. Hamzeh, (2009) conducted a computer simulation study to understand the relationship between Tasks Anticipated (TA) in Look Ahead Planning and overall project duration. TA is a metric used to assess the ability to accurately predict tasks that will occur within the next two to three weeks. The simulation involved the addition of 'New Tasks' in the Weekly Work Plan of Look Ahead Planning. These new tasks were not a part of the Look-Ahead Planning and were not broken down or made ready systematically. Their appearance was believed to be caused by a lack of foresight and was presumed to add an extra burden to the planning process. The reasons behind the emergence of these 'New Tasks' were studied by (Rouhana & Hamzeh, 2016) and have been categorized as issues related to planning, issues related to ongoing construction, and uncertainties.

LPS PLANNING BEHAVIOURS

Gomez et al. (2019) explored the concept of Behaviour Based Quality, which suggests that the behaviours of individuals in an organization are influenced by the consequences they experience. This motivates project teams to behave in a way that produces the desired outcomes. Organizational behaviours are also affected by Respect for People and Psychological safety, a term coined by Amy Edmondson in 1999, which supports an individual's power of speaking the truth, making suggestions and asking for help knowing that the mistakes will be met with help rather than punishment. This concept supports the Lean principle of reliable promise-making in the Last Planner System (Ballard et al., 2009).

Fauchier et al. (2013) connected the behaviours arising from the implementation of the Last Planner System and found that LPS promotes the formation of a social network with improved coordination. Organizations that adopt LPS exhibit a higher level of trust among members and create a social system with an increased flow of information. Key behaviours observed in LPS-implementing organizations include collaboration, long-term planning, pull planning, look-ahead planning, commitment planning, constraint identification, making tasks ready, measuring performance, root-cause analysis and corrective actions (Aslesen & Tommelein, 2016; Laufer et al., 1992; Hamzeh & Aridi, 2013; Hunt & Gonzalez, 2018; Perez & Ghosh, 2018; Viana et al., 2010).

SOCIAL INTERACTIONS & SOCIAL NETWORK ANALYSIS

The decision-making process in an organization is directly affected by social interactions and communication between the different team members. The interactions between participants can be both task-based and relational. Task-based interactions involve the discussion of ideas, opinions, and suggestions related to a specific task, while relational interactions involve interactions for demonstrating support, establishing values, and resolving differences (Wang et al., 2018). Ghosh et al. (2019) analysed two healthcare construction projects, one implementing LPS and the other using traditional planning practices, and found that the former showed a higher level of trust among the members and created a social system with a better flow of information.

Social Network Analysis (SNA) is a widely adopted research tool that is used to analyse the interactions and relationships among project participants involved in the LPS implementation at a construction project site. The use of Social Network Analysis (SNA) enables the capturing of valuable information and communication that takes place informally in an organization. Alarcón et al. (2013) highlight the ability of SNA to analyse social relationships and interactions that are task-based or relational. It allows for mathematical and graphical analyses of otherwise essentially qualitative data in the form of nodes and edges. The nodes represent an individual or organization. The connections between these nodes, called edges, represent the transfer of material resources, associations or affiliations, behavioural interactions, information or knowledge transfer or conflict resolutions. By assuming that individuals in an organization are independent, SNA provides metrics to quantify the otherwise invisible flow of information (Pryke, 2012). Some of the metrics used in SNA are:

Network Density: This is the measure of the total number of connections between nodes in a given network to the total number of maximum possible connections. This value falls between 0 to 1. The network density can be used to define the fragmentation of a project team and the degree to which the project participants are connected.

Network Diameter: This defines the maximum number of links required to connect two diverse nodes in the network. It is the longest of all calculated path lengths and gives the measure of how far the information has to travel to reach all nodes.

Average Path Length: This averages the shortest possible path between all nodes and provides a measure of the communication efficiency in the network.

Network Degree: This represents the average number of links per node. A node that has a large number of connections may have significant influence and access to information.

Centrality: This is used to highlight the most important node and its strategic positions in the network. It can be defined by degree centrality, closeness centrality and betweenness centrality.

SNA can be used for different problems that the planners face related to coordination, cooperation and trust; power and influence; organizational levels; informal organizations; information flow; and dynamic network development (Dempwolf & Lyles, 2012). It addresses the relationship patterns over time, and in turn describes how these patterns affect behaviours (Wang et al., 2018). SNA has become a prominent tool for understanding the informal interactions between the project participants and their consequent information flows in construction projects implementing the Last Planner System. (Herrera et al., 2018; Castillo et al., 2018; Priven & Sacks, 2015; Abbasian-Hosseini et al., 2015; Cisterna et al., 2018)

RESEARCH METHODOLOGY

The research adopted a mixed-method approach combining interpretive (qualitative) and positivist (quantitative) methods to address the research questions. The data has been collected using both qualitative and quantitative approaches and includes case studies, questionnaire surveys and direct observation at the construction sites. Social Network Analysis is adopted as a research tool to study the formal and informal communication networks between the project participants with an intent of understanding the collaboration and coherence as organizational behaviours. Three case studies were selected to understand the behaviours and attitudes of project participants that eventually lead to the emergence of New Tasks. The use of multiple case studies, each supporting the phenomenon of the emergence of New Tasks and the subsequent social networks formed, help achieve triangulation in the research. The rationale has helped in ameliorating the internal and external validity of the research. Data was collected through primary sources, such as interviews and questionnaire surveys, and secondary sources, such as Look-Ahead plans and meeting records from the case studies.

As the research predominantly deals with informal networks built on social conventions rather than a formal binding contract, a *realist approach to boundary specification* in the Social Network Analysis has been applied. In this approach, the boundary networks are defined by the nodes (individuals) themselves. For example, a few individuals who are interviewed would identify other nodes with whom they would have to interact to achieve the project objectives (Pryke, 2012). The questionnaire survey for SNA was designed in a way that allowed the participants to list names of people with whom they interact regarding LPS. The questionnaire was further filled out by the people identified through the survey thus completing the interaction network.

The respondents chosen for the questionnaire were individuals involved in the look-ahead planning and the weekly planning of the Last Planner System in the projects selected for the case study. The links between the two nodes consisted of their formal and informal interactions. The data collection included the traditional approaches of surveys, interviews and direct observations and the use of big data of a passive nature including meeting minutes and timesheets. The collected data were edited, coded and translated into the SNA language. Data analysis was performed using Gephi, version 0.9.2, a multiplatform free software used for creating social network metric graphs. This software was used for both the graphical representation of the networks formed and the calculation of SNA metrics. The edges were defined using a source and a target, indicating the information flow between nodes.

The nature of interaction obtained from the survey was categorized into three LPS planning behaviours and the frequency of interaction was used to assign the weights to the edges. The paper investigated planning behaviours observed on the case study projects and those reported in the literature. Behaviours of similar nature were aggregated into one group; for example, all 'planning' behaviours such as updating the master plan, look-ahead planning and commitment planning were grouped into the 'Planning & Commitments' family. Similarly, two other groups, 'Constraint Analysis' and 'Continuous Improvement' were defined. The grouping was performed for convenience, was non-comprehensive and was solely based on the author's reasoning. Table indicates the planning behaviour categories and the weights decided for the analysis.

A cross-case analysis was performed to compare the number of New Tasks that emerged in each project. A scatter diagram was plotted to relate the percentage of New Tasks that emerged in each case study to the network cohesiveness represented by the network density. This gives a cause-and-effect relationship between the two parameters and is used to conclude the research.

Table 1: SNA Planning Behaviors & Edge Weights

Nature of Interaction	Planning Behaviour	Frequency of Interaction	Weight
Updating Master Plan	**Planning and Commitments**	Monthly	1
Look Ahead Planning		Fortnightly	2
Commitment Planning		Weekly	3
Constraint Analysis and Removal	**Constraint Analysis**	Daily	4
Problem-Solving		More than once daily	5
Corrective action of Non-completed Tasks	**Continuous Improvement**		
Decision Making			

CASE STUDIES

Three case studies were chosen for the exploratory part of the research and New Tasks were observed for six weeks during the study. The organizations chosen for the case studies had been implementing lean practices, specifically the Last Planner System for over a year ensuring a high level of lean maturity and the successful overcoming of initial cultural barriers in the implementation process. Each of the three selected projects had a planning system in place, with a designated planning engineer responsible for maintaining regular updates to the look-ahead and weekly plans. The case studies were selected to represent different sizes and scales, including one large-scale, one medium-scale, and one small-scale project, with the first two case studies being from the same organization and the third from a separate organization. Table 2 presents the location, type and size of the project, lean tools adopted, look-ahead planning duration and the total number of planned and New Tasks.

Table 2: Description of Case Study Projects

Case Study	1	2	3
Location	Mumbai, India	Khalapur, India	Ahmedabad. India
Built-up Area	93,000sqm	306,500sqm	56,000sqm
Project Type	Residential	Industrial Mega Park	Residential
Lean Tools Adopted	LPS, Work Sampling, Value Stream Mapping	LPS, Value Stream Mapping, Work Sampling	LPS
Look Ahead Planning	6 weeks	6 weeks	4 weeks
Planned Tasks	225	270	220
New Tasks	39	61	71

In all case studies, based on the secondary data collected from the site in the form of weekly plans and look-ahead schedules, a comprehensive list of 'New Tasks' that emerged within six weeks of site execution was prepared.

CASE STUDY 1

The project was chosen because the organization had been implementing lean since 2011 in facilitation with ILCE (Institute of Lean Construction Excellence), IIT Mumbai and IIT Madras. The data for the SNA questionnaire survey was gathered from individuals involved with the Last Planner System of the case study. The questionnaire for SNA was completed by 20 respondents involved with different stakeholder groups in the Big Room Meetings. In Case Study 1, 39 New Tasks emerged from a total of 225 tasks planned for each of the six weeks. Lack of communication between the project team was the cause of most New Tasks and delays at the site. A few other reasons were lack of coordination, improper task sequencing, clash detection at the site and unexpected arrival of information. The emergence of New Tasks had a direct impact on the Percentage Plan Complete (PPC), as tasks that were not constraint-free could not be completed in the execution week. Deploying resources on the New Tasks that emerged caused the incompletion of the already planned tasks in the Weekly Work Plan.

CASE STUDY 2

The implementation of the Last Planner System in the project began in 2018, with senior management leading the effort and with guidance from IIT Mumbai and IIT Madras. Each industrial plant within the project had its separate implementation of the LPS. The project made use of Big Room Meetings and Steering Committee Meetings to help with planning. The biggest challenge in the effective planning of this project was the involvement of multiple stakeholders in the form of customers and the complexities in their requirements. The data for the SNA questionnaire survey was completed by 15 participants involved in the Last Planner System. Case Study 2 accounted for a total of 61 New Tasks from 270 tasks planned for the six weeks of study. The New Tasks emerged mostly due to inefficiencies in the planning of the project. The scope of work was not clear from the client's end and there were multiple design revisions causing rework on the site leading to New Tasks. Similarly, when unplanned material was delivered to the site, additional tasks were added.

CASE STUDY 3

The organization had been practising lean construction, particularly the Last Planner System (LPS), since 2018. The project blended traditional practices, such as the Critical Path Method (CPM), with the lean practice of LPS. The planning software used for this project was Microsoft Project and an in-house software developed by the organization was used to update the weekly and daily reports. Unlike the first two case studies, the look-ahead plan was not prepared collaboratively by mapping out the constraints and taking inputs from all the vendors assigned for different work packages. The weekly work plans were prepared by the supervisors on-site, but since the work was based on a repetitive cycle, these plans did not change radically from one week to another. The supervisors added comments about some details and the constraints that might occur during the week. The data for the SNA questionnaire survey was completed by 12 participants involved in the Last Planner System. Case Study 3 had a total of 71 New Tasks from a total of 220 planned tasks over the six weeks of study. Some of the reasons for the emergence of these tasks were lack of coordination, unexpected completion of previous work and the addition of labours at the site.

SOCIAL NETWORK ANALYSIS

The behaviours related to the occurrence of New Tasks were analysed through Social Network Analysis (SNA) to understand the interaction patterns between individuals involved in the Last Planner System (LPS) approach. The SNA data was both qualitatively and quantitatively interpreted. The planning behaviours were compared qualitatively based on the SNA maps created for each case study, as shown in Figure .

It can be seen that the social network patterns for the 'Planning and Commitments' network of Case Study 1 form almost a geodesic structure implying strong connections among the members of the network. The network maps for Case Study 2 show some cohesiveness while Case Study 3 has a greater number of isolates. The 'Constraint and Problem-Solving' network corresponds to the process of constraint analysis and removal between different team members of an LPS organization. The network diagrams for Case Studies 1 and 2 show stronger cohesiveness than Case Study 3. This can be attributed to the daily constraint removal between the subcontractor groups in Case Studies 1 & 2 compared to Case Study 3 where constraints were only removed when the problems arose. In Case Study 1, all project actors had similar *network degrees* implying that all members participated in the process of constraint analysis. For the 'Continuous Improvement' network, all three case studies exhibited little cohesiveness and had a small number of nodes. Only the members at a higher level in the hierarchy participated in this process. The emergence of repetitive New Tasks across six weeks in all three cases can be attributed to poor involvement in the continuous improvement process.

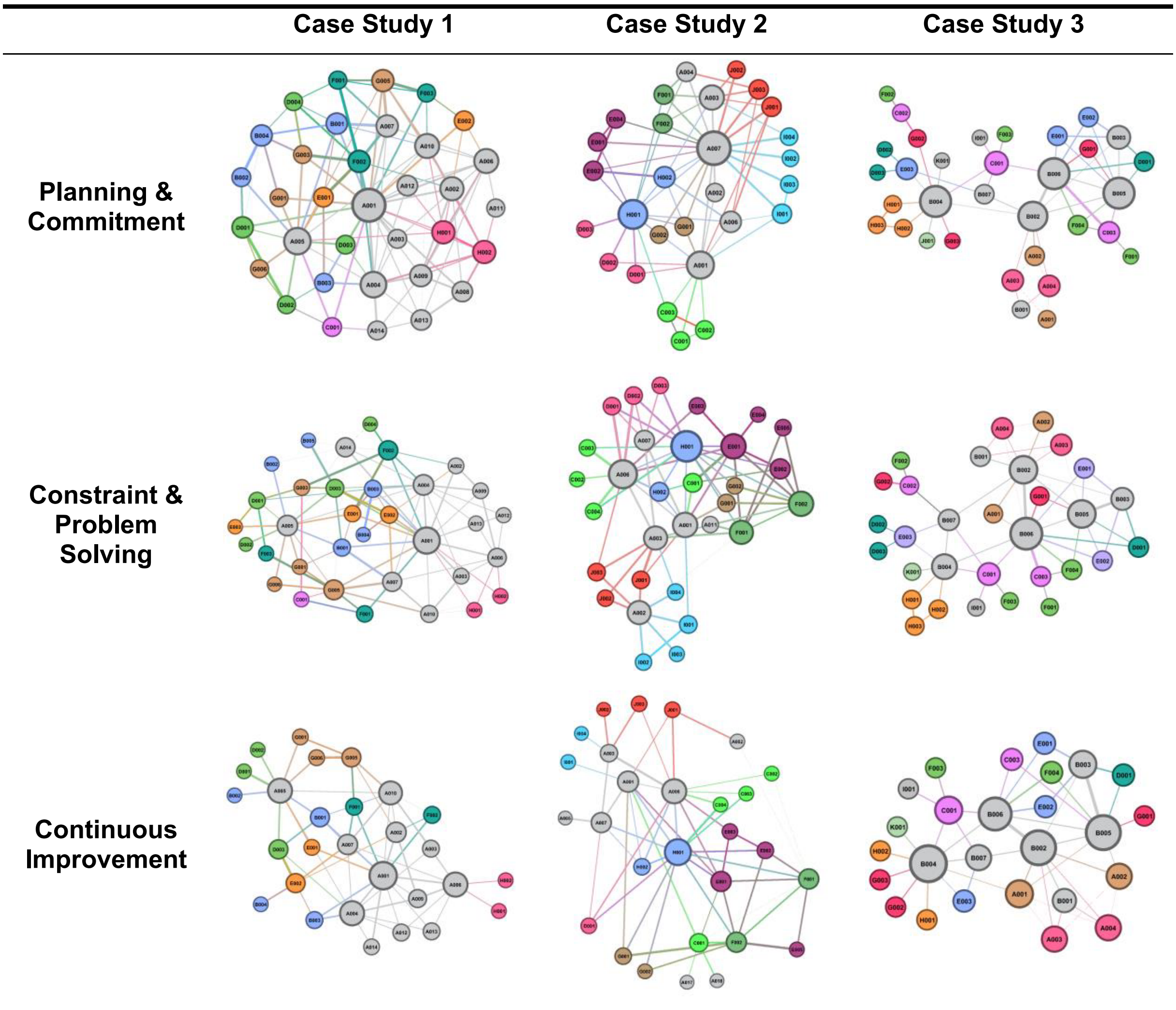

Figure 1: SNA Qualitative Comparison

The quantitative SNA used metrics like density, average degree, average path length and diameter. A single network map for each case study was prepared to perform this analysis to provide a comprehensive overview. Table presents a comparative analysis of all the network metrics. Network Density is the ratio of all the links present in the network to the total number of possible links. The unweighted density of Case Study 1 was 0.20 which signifies that 20% of the network was connected while for Case Studies 2 and 3 the values were 16% and 11% respectively. Since the number of nodes in all three networks was similar, higher network density could be correlated to higher cohesiveness and communication efficiency.

The Average Degree of all the nodes can be used to measure the structural cohesion of the network. The results for the same are in line with the average density as Case Study 1 had the highest average degree of 5.78 indicating a much more strongly connected network than the other two cases. Case Study 3 had the lowest average degree of 3.76. This can be understood by looking at the network map that has a higher number of isolates.

The Average Path Length is an indicator of communication efficiency. The path length was lowest for Case Study 2 and highest for Case Study 3. Since the members of Case Study 3 were connected only through the planning engineers and the project managers, any information would have to pass through them before it can be communicated to the entire network. The Diameter indicates the longest path for the information to reach all members. In Case Studies 1 and 2, any information had to pass through a maximum of 4 members to reach the entire network, while in Case Study 3, the diameter was 6.

Table 3: SNA Metrics Comparison across Case Studies

	CASE STUDY 1	CASE STUDY 2	CASE STUDY 3
Nodes	36	39	33
Edges	104	113	62
Density	0.20	0.16	0.11
Average Degree	5.78	4.36	3.76
Average Path Length	2.19	2.17	2.71
Diameter	4	4	6

The cross-case analysis helps establish the relationship between the New Tasks that emerged and the different planning behaviours observed at the site. To compare the New Tasks between the three case studies, a percentage measure was created. The percentages of New Tasks in the three case studies were 17.3%, 22.6% and 32.3% for Case Studies 1, 2 and 3 respectively.

A correlation between the percentage of New Tasks observed in each project with the density of the network helps to establish a cause-and-effect relationship between the communication efficiency in a network and the number of New Tasks that arise. Average Density was used for the correlation as it is independent of the number of members in each network. All other network metrics are absolute and depend upon the total number of project participants. As observed in Figure , the percentage of New Tasks was inversely proportional to the network density. The networks with higher density had fewer New Tasks and vice versa. This is related to the communication efficiency in the three networks. The emergence of New Tasks in each case was due to a lack of communication and collaboration between the project participants.

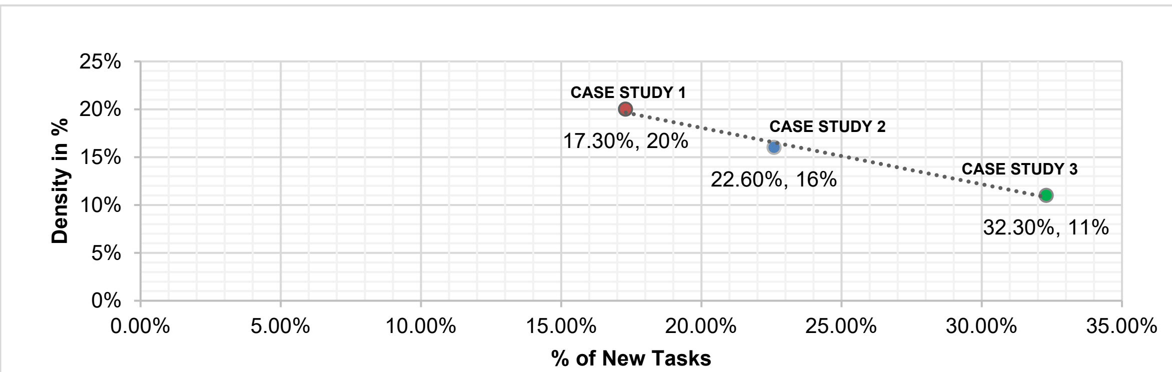

Figure 2: Correlation between Network Density and New Tasks

CONCLUSIONS

It was seen from the literature survey that the implementation of the Last Planner System in an organization engenders a social network among the members that enhances coordination. Three different organizations with varying degrees of LPS implementation were studied to evaluate the New Tasks that emerged during execution. SNA metrics like density, diameter, average path length and average degree were used to analyse the different case studies based on the planning behaviours they exhibit. The comparison of SNA results showed a relationship between the number of New Tasks that emerged during the six-week study period and the total number of planned tasks in each project. The following interpretations can be made from the research:

The inverse relationship between the percentage of New Tasks and the network density in the case studies highlights the importance of effective communication and collaboration among project participants. A higher network density, indicating better communication and efficient flow of information, is associated with fewer New Tasks.

The case studies presented highlight instances where unplanned and ad hoc tasks were added to existing tasks, leading to disruptions in the planned project schedule and impacting the project performance. It is important to acknowledge that the observed ad hoc reactionary behaviours were a result of the lack in systematic implementation of LPS, hence, there is a need for a robust LPS process to mitigate such issues.

Look-Ahead Planning is key in this regard as it enables collaboration between all the stakeholders in pull planning of the Tasks to be planned. The constraints are identified and resolved at this stage and the tasks are made ready for implementation. This reduces planning errors due to communication inefficiencies to a great extent.

This paper proposes a gradual increase in the authority and capability of subcontractors and foremen to participate in planning processes, with a focus on Look-Ahead Planning. The Last Planner, typically the foreman, has the ability to ensure a consistent and predictable flow of work downstream. However, cultural and language barrier can be a challenge in implementing LPS. Foremen and other workers who are not fluent in the language used in meetings may have difficulty understanding instructions and expressing their ideas. This can lead to misunderstandings, delays, and errors in the planning process. To overcome these barriers, it is important to provide training and education to all participants in LPS, including foremen and workers who may be less familiar with the planning process.

The findings from the case study research cannot be generalised for the entire construction industry as only specific planning behaviours are compared, not the overall projects. The research mentions the reasons for the New Tasks but does not provide insight into their impact on the time or cost of the project. Only the New Tasks that emerge due to deficiencies in the planning system have been included in the comprehensive list prepared. Those occurring due to uncertainties like weather changes or equipment breakdown have not been considered for the research. While performing Social Network Analysis, it has been assumed that the network graphs prepared at one point of time in the research are representative of the social interaction patterns for the six weeks of study. There is significant potential for future research to examine the impact of new tasks in weekly plans and their relationship with weekly PPC trends. Additionally, the application of Social Network Analysis could be expanded to the organizational level to investigate interaction patterns surrounding the emergence of New Tasks.

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DEVELOPMENT OF A MACHINE LEARNING-BASED LABOUR PRODUCTIVITY PREDICTION TOOL TO PRACTICE LEAN CONSTRUCTION

Abhay Saini[1] and Albert Thomas[2]

ABSTRACT

The construction industry is a labour-intensive industry. This is one of the reasons why the industry has significant room to incorporate lean principles and reduce waste. Various lean tools can be implemented in construction projects, such as Kanban, JIT and 5S. However, these tools majorly focus on activities at an aggregate level and do not always incorporate sub-activities carried out within a small activity. The productivity of smaller activities (activities that typically span from minutes to hours) is essential to be assessed and controlled to increase the efficiency of overall activity. This paper aims to develop a labour productivity prediction tool based on machine learning principles and lean ideologies to improve the overall productivity of construction activities, considering the productivity of sub-activities. The developed framework is demonstrated by analyzing the productivity of reinforcement activity in a construction project. In the study, inventory wastes are minimized using the prediction from the developed quantitative labour productivity prediction model. An increase of 13.7% in overall productivity is achieved through the implementation of the developed framework.

KEYWORDS

Lean construction process, value stream mapping, machine learning, lean theory

INTRODUCTION

The construction industry is a labour-centric industry, and it may remain the same in the coming decades. The growth of the industry and the subsequent infrastructure growth depend heavily on completing projects on time and as per the planned cost (M. Hafez, 2014). 30%-50% of the total cost of construction projects is only spent on labour costs (Asadullah Tahir et al., 2015), and therefore achieving optimum labour productivity is crucial to prevent time and cost overruns. There are several approaches to predicting labour productivity in construction projects. These studies can be categorized into four, as given below.

1. The time-series analysis method involves historical data on productivity levels over time to identify trends and patterns that can be used to make predictions about future productivity. (Song and Abourizk, 2008)
2. Project benchmarking involves comparing the productivity of a particular project to those of similar projects and using this information to make predictions about future productivity. (Abdel-Razek et al., 2007)

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3. Surveys and expert opinions involve gathering information from experts in the field or from workers themselves to make predictions about future productivity. (Shehata and El-Gohary, 2011)
4. The machine learning and artificial intelligence approach involve using algorithms and computational methods to analyze large amounts of data and predict future productivity based on that analysis. (Heravi and Eslamdoost, 2015)

Even though four of these approaches are available to estimate productivity, it is also important to note that a combination of these methods is often used to make the most accurate predictions about labour productivity. The estimation of labour productivity for any given activity is typically achieved by calculating the ratio of total output to total input, where input can be measured as either the total number of hours worked or the total number of workers involved. Alternatively, multifactor productivity, which accounts for both labour and capital inputs, can also be used as a measure of labour productivity (Rojas and Aramvareekul, 2003).

While these methods provide accurate measures of productivity for tracking ongoing projects, they pose challenges when attempting to predict the productivity of an activity that is still in progress. For instance, the total output of such an activity may be zero, but the work remaining to complete the activity may not be equivalent to the initial work remaining. This discrepancy can occur in practice when certain steps of the activity have been completed but do not contribute value to the project, resulting in a calculated productivity of zero. Although this consideration may not impact the actual performance of the site, it can significantly affect the planning and management of the remaining activities. Thus, it is important to carefully account for such nuances in productivity calculations for accurate project planning and management. Once the prediction of productivity is achieved for an activity, we can use it to implement lean in that construction activity.

Lean-based techniques are also employed to improve labour productivity in the construction industry. The various tools and techniques to implement lean in construction projects include 5S, Just in Time (JIT) and Kanban, work sampling, value stream mapping, Poke-Yoke, Takt-Time, and Kaizen with waste minimization as the key objective (Leksic et al., 2020, Singh and Kumar, 2020, Cossio and Cossio, 2012.; Sundararajaan and Madhavi, 2018; Tommelein and En Yi Li, 1999). The first step in the implementation of these tools is to identify the wastes involved and perform various analyses such as Pareto chart, failure mode and effects analysis (FMEA), process improvement and variation reduction to improve the process (Banawi and Bilec, 2014). Understanding labour productivity plays a major role in implementing lean and reducing waste in the construction industry (Serpell et al. 1994). Therefore, it is essential to estimate the actual productivity by assessing the effects of various influencing factors.

Even though the traditional productivity estimation techniques mentioned earlier and lean-based solutions have provided approaches to quantify productivity, there is a need to accurately predict the productivity of construction activities while they are being performed by also considering the power of lean construction. This study, therefore, proposes a novel framework to predict the absolute productivity of any activity, regardless of its current stage of completion. To achieve this, the study employs breaking down the activity into smaller sub-activities, enabling precise prediction of absolute productivity by also incorporating non-value-adding yet essential steps in productivity prediction. This is a notable improvement over traditional approaches that often exclude such steps. Furthermore, the study discusses the potential use of the framework in implementing the lean principle, which aims to reduce waste and optimize efficiency in the activity under consideration. This novel framework presents a promising approach to accurately predict and optimize productivity, offering potential benefits for various industries and applications.

LITERATURE REVIEW

Studies on labour productivity in construction typically focus on factors that impact labour productivity and methods for improving it. Several studies have found that the construction industry has low labour productivity compared to other sectors (Dixit et al., 2018; Rojas and Aramvareekul, 2012.), and this is due to several factors, such as poor project planning and management, a lack of standardization and modularization, and the inherent complexity of construction processes (Agrawal and Halder, 2020). Further, the factors that have been shown to impact labour productivity in construction include worker skill levels, job site conditions, the use of equipment and technology, and the availability of materials.

Some studies have also highlighted the importance of worker motivation and job satisfaction and have found that these factors can have a significant impact on labour productivity. Mistry and Bhatt (2013) conducted a survey in Gujarat, India and categorized the factors into four categories and found that the most affecting factors influencing productivity are the outside weather and delay in payment. Similarly, Doloi et al. (2012) selected fourteen factors and tried to develop a predictive model for labour productivity using Artificial Neural Network (ANN), adaptive-network-based fuzzy inference system (ANFIS), ANFIS-Genetic Algorithm and Random Forest algorithms. In this study, a predefined rating between one to five was taken for the factors. Likewise, Thomas and Sudha Kumar (2015) conducted an Indian case study for the same and explored the effects of some external factors, such as political instability, on labour productivity. Similarly, Enshassi et al. (2007) conducted their study in the Gaza Strip and concluded that work front unavailability is the top most factor that affects labour productivity, followed by a lack of proper planning. Overall, it can be seen that the site layout, crew composition and management-related factors are primarily found to affect labour productivity (Alaghbari et al., 2019; Doloi et al., 2012; Enshassi et al., 2007; Hamza et al., 2022; Hiyassat et al., 2016; Makulsawatudom et al., 2004; Nyoni and Bonga, 2016; Thomas and Sudhakumar, 2015). However, all these factors are exclusive of on-site tangible factors that directly influence the productivity of an individual activity. For instance, the different shapes of formwork in the formwork activity and cutting and bending length in the reinforcement activity. Several approaches can be witnessed in the literature about measuring the labour productivity of construction projects, but there are very limited studies on finding out the absolute labour productivity of any activity by incorporating all sub-activities.

Various studies have also found that construction labour productivity can be improved through better project management practices, such as the use of building information modelling (BIM) technology and the implementation of lean construction methods (Poirier et al., 2015) by streamlining construction processes, reducing waste, and improve communication and collaboration among stakeholders. Waste in construction can manifest in various forms, including overproduction, waiting, unnecessary movement, carrying excess inventory, and rework (Abbasian, Nikakhtar et al., 2012). Time studies and different process analysis techniques have been utilized to systematically identify and quantify waste in the construction process (Suresh, 2013). After identifying waste and its underlying causes, the next stage is to identify cost-effective opportunities for improvement that can be applied to reduce waste and improve productivity. This analysis is typically carried out through collaborative teamwork and brainstorming among team members (Serpell et al., 1994).

Overall, there is a need for a quantitative model that can predict labour productivity by incorporating the sub-activities and help implement lean techniques at construction sites. Therefore, this study presents a framework to predict absolute labour productivity for an activity. The two objectives of this study are given below.

1. To develop a machine learning-based labour productivity prediction framework based on the productivity of sub-activities that can help in tracking and re-arranging the flow of the activity.

2. To utilize the result of the framework to implement lean principles in the activity to increase its efficiency.

RESEARCH METHOD

To achieve the above objectives, a three-stepped research methodology is adopted that includes construction activity selection and analysis, productivity predictivity model development and the model's output to implement the lean principle.

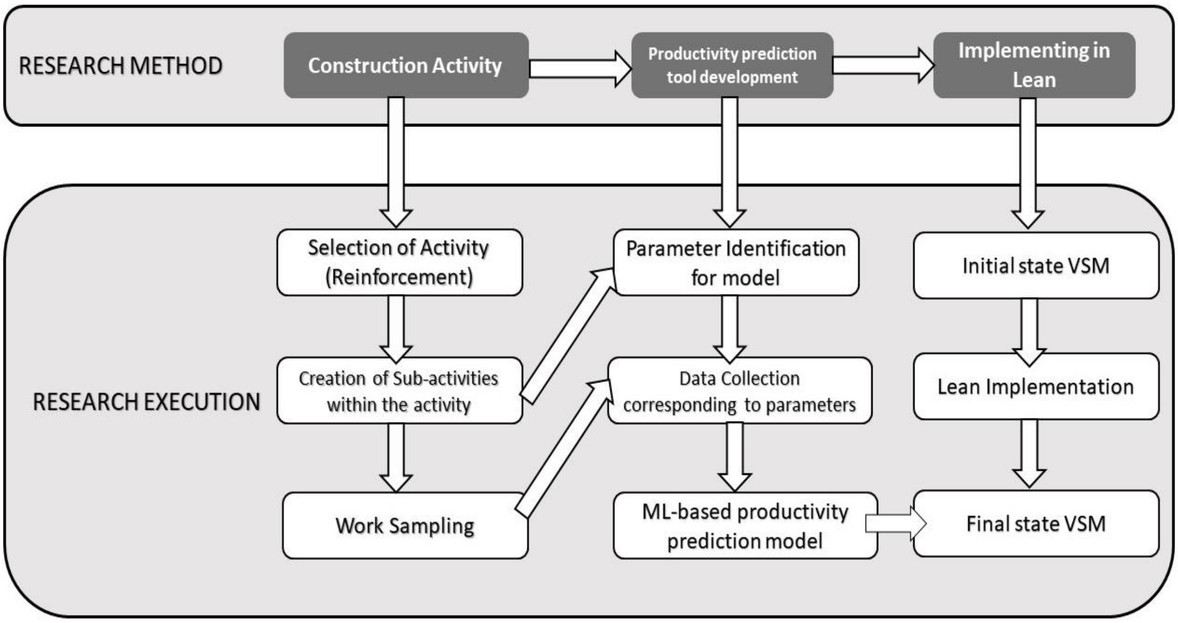

Figure 1: Research Methodology

The first step in research execution is analyzing a case study activity in detail and creating sub-activities. Activity is divided into sub-activities by capturing the actions that take significant time. By observing each sub-activity, the parameters that are affecting productivity are identified. Further, work sampling is performed for the entire cycle of the activity to collect relevant data for developing the machine learning-based multivariate linear regression method-driven predictive model for labour productivity using the parameters identified. A Value Stream Mapping (VSM) approach is then used to develop the detailed step-wise value stream map of the current state. Further, using the productivity values predicted by the productivity prediction tool earlier, a modified VSM is also developed. The detailed steps in identifying the sub-activities, work sampling, ML model development and performing VSM are explained below.

DIVIDING ACTIVITY INTO SUB-ACTIVITIES

The framework is applied at residential high-rise building construction sites in Mumbai. Reinforcement activity is analyzed, and it is then divided into sub-activities. This categorization is carried out based on the observation on site where the major time taking tasks are termed as sub-activities.

Table 1: Sub-activity categorization

Reinforcement Activity	
Sub-activity 1	Shifting and Cutting of Rebar
Sub-activity 2	Bending of Rebar
Sub-activity 3	Shifting to Workplace
Sub-activity 4	Laying and Fixing of Rebar
Sub-activity 5	Tying of Rebars

WORK SAMPLING

Once the sub-activities are formed, work-directed sampling is carried out to register the value of each activity in the sub-activities. This method involves observing employees performing specific tasks or activities. Observers record the activities being performed, and the data is later analyzed to determine the proportion of time spent on different tasks. The same is tabulated in the following table 2.

Table 2: Work Sampling for Reinforcement Activity

Sub-Activity	State
Cutting of Rebar	Shifting rebar to the cutting tool
	Measuring and cutting
	Shifting rebar to inventory 1
Bending of Rebar	Shifting rebar to bending Tool from inventory 1
	Measuring and bending
	Shifting rebar to inventory 2
Shifting to Workplace	Crane comes down from the 4^{th} floor
	Idle time
	Crane loading
	Idle time
	Crane going up to the 4^{th} floor
Laying and Fixing of Rebar	Shifting and laying of rebars
	Measuring and fixing rebar
	Idle time
Tying	Tying of rebars

PARAMETERS IDENTIFICATION

For the development of the absolute productivity prediction tool, input parameters are required. The parameters that are affecting productivity are shown below in Table 3. These parameters are tangible parameters collected from the construction site by visual inspection. Data is taken from a high-rise building construction site in Mumbai. Qualitative data are not considered here, so the productivity received is the absolute productivity for the considered activities.

Table 3: Identified Parameters table

Sub-Activity	Parameters
Cutting of Rebar	Number of rebars in one movement
	Diameter of the rebar
	Cutting the length of rebar
	The total length of the rebar cut
	Number of workers in the crew
	Weight of the rebar cut
	Percentage of skilled worker
	Time taken
Bending of Rebar	Number of rebars in one movement
	Diameter of the rebar
	The total length of the rebar cut
	Number of bends
	Number of workers in the crew
	Weight of the rebar bend
	Percentage of skilled worker
	Time taken
Shifting to Workplace	Height of the destination inventory
	Distance from crane placed to inventory
	The weight of the rebar shifted.
	Weight of the rebar bend
	Percentage of skilled worker
	Time taken
Laying and Fixing of Rebar	Diameter of the first type of bars
(Two different diameter rebars were used)	Diameter of the second type of bars
	Number of reinforcement bars of the first diameter
	Number of reinforcement bars of the second diameter
	Length of reinforcement bars of the first diameter
	Length of reinforcement bars of the second diameter
	The total length of reinforcement bars of the first diameter
	The total length of reinforcement bars of the second diameter
	Number of bends of reinforcement bars of the first diameter
	Number of bends of reinforcement bars of the second diameter
	Number of workers in the crew
	Weight of the rebar cut
	Percentage of skilled worker
	Time taken
Tying	Number of rebar joints tied
	Time taken

REGRESSION MODEL DEVELOPMENT

Regression models are developed using the above-mentioned parameters as input and the time required to carry out the sub-activity as an output. The first regression model for the cutting sub-activity is shown here. The input parameters shown as x1 to x5 are the diameter of the rebar, cutting length, rebar initial length, number of cuts and weight. The output parameter is the time required to carry out the sub-activity. A summary of the model is presented below in Figure 2.

```
0s [3]
                            OLS Regression Results
==============================================================================
Dep. Variable:                      y   R-squared:                       0.949
Model:                            OLS   Adj. R-squared:                  0.945
Method:                 Least Squares   F-statistic:                     292.1
Date:                Mon, 03 Apr 2023   Prob (F-statistic):           2.05e-49
Time:                        06:29:22   Log-Likelihood:                -419.96
No. Observations:                  85   AIC:                             851.9
Df Residuals:                      79   BIC:                             866.6
Df Model:                           5
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const        219.5790     68.473      3.207      0.002      83.286     355.872
x1         -1.023e-13      2.339  -4.38e-14      1.000      -4.655       4.655
x2            79.7540     16.926      4.712      0.000      46.063     113.445
x3             1.2483      1.853      0.674      0.502      -2.439       4.936
x4            -5.3671      8.288     -0.648      0.519     -21.865      11.130
x5          5.384e-15      0.395   1.36e-14      1.000      -0.786       0.786
==============================================================================
Omnibus:                        2.028   Durbin-Watson:                   2.809
Prob(Omnibus):                  0.363   Jarque-Bera (JB):                1.939
Skew:                          -0.361   Prob(JB):                        0.379
Kurtosis:                       2.837   Cond. No.                     1.06e+03
==============================================================================
```

Figure 2: Regression Model Result for Cutting Sub-activity

From Figure 2, we find the R-squared value as 0.949. That shows a good fit of the graph for the data entered. Eighty-five observations were used to develop this model.

IMPLEMENTATION AND RESULTS

The developed model is used to implement lean principles in the reinforcement activity. Value Stream Mapping (VSM) is used as a lean tool in this study. A current state VSM is developed from site observation which provides a snapshot of the current activity. Usually, in a VSM method, further, a future state would be developed based on assumed productivity values. Here in this study, the model developed above will be used to predict the productivities to be considered for developing the final state VSM.

CURRENT STATE VALUE STREAM MAPPING

For developing the current state VSM, a reinforcement activity is observed on the construction site. Data for developing the VSM is collected for each of the sub-activities, including idle time and wastage. The data collected is for 8.87 kg of rebar having a diameter of 10 mm and five bends. Figure 3 below shows the current state of the observed process.

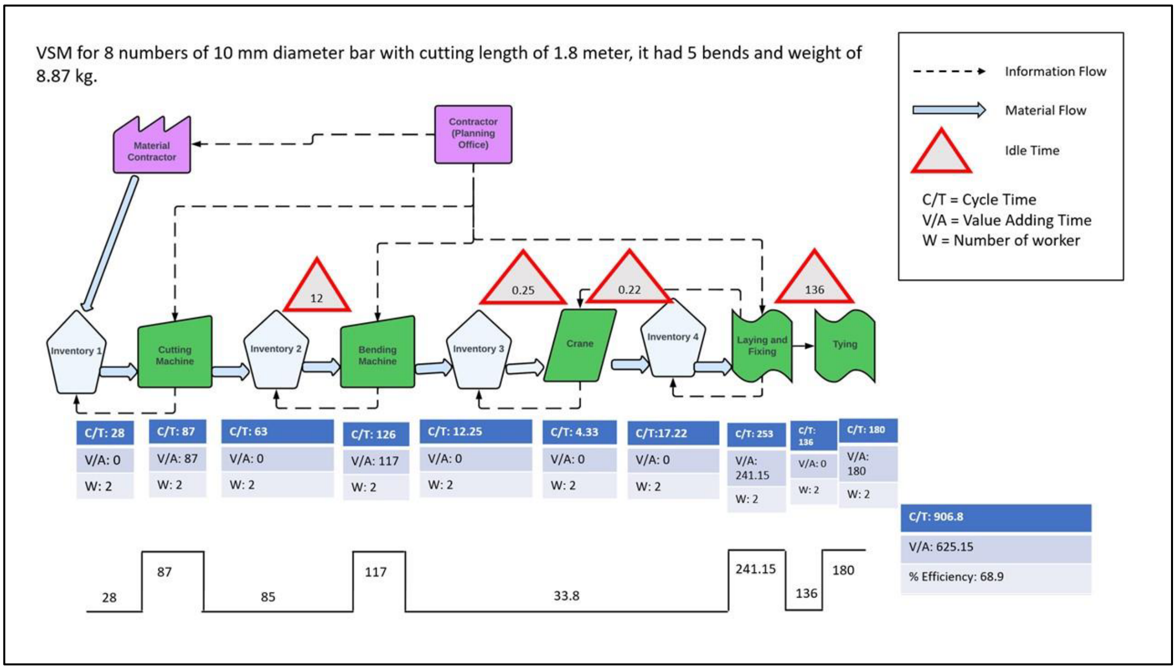

Figure 3: Current State VSM Diagram

PRODUCTIVITY OF EACH SUB ACTIVITY

For predicting the productivities of the sub-activities, multivariable linear regression is applied considering all the parameters shown above. The prediction was carried out for the same rebars in the current state VSM. Table 4 provides the details of predicted productivity values that are used to develop the future state VSM.

Table 4: Productivity prediction using regression analysis

Sub Activity	Workers in Crew	Productivity (kg/hr/crew)	R^2	Observations
Cutting	2	120.2	0.948	85
Bending	2	90.17	0.943	85
Shifting (Crane)	3	7673	-	17
Laying and fixing	2	51.43	0.915	85
Tying	2	147.8	-	35

As per the productivity obtained by the study, there are significant differences between the productivity of sub-activities. So, to remove some of the inventory from the current state of VSM, we need to match the productivity of sub-activities. That will make the activity more efficient as the material can be shifted to the sub-activity without going to inventory.

Here it can be seen that the productivity of cutting is 120 kg/hr and that for bending is 90 kg/hour, so if four crew for bending and three crew for cutting are assumed, the productivity of the process will be the same, and materials could be directly shifted to bending after cutting without using an inventory. In addition, after reducing the idle time, the final state VSM is proposed below, which is developed using the predicted productivity values.

PROPOSED FINAL STATE VALUE STREAM MAPPING

The final state VSM is developed using the predicted productivity values given below.

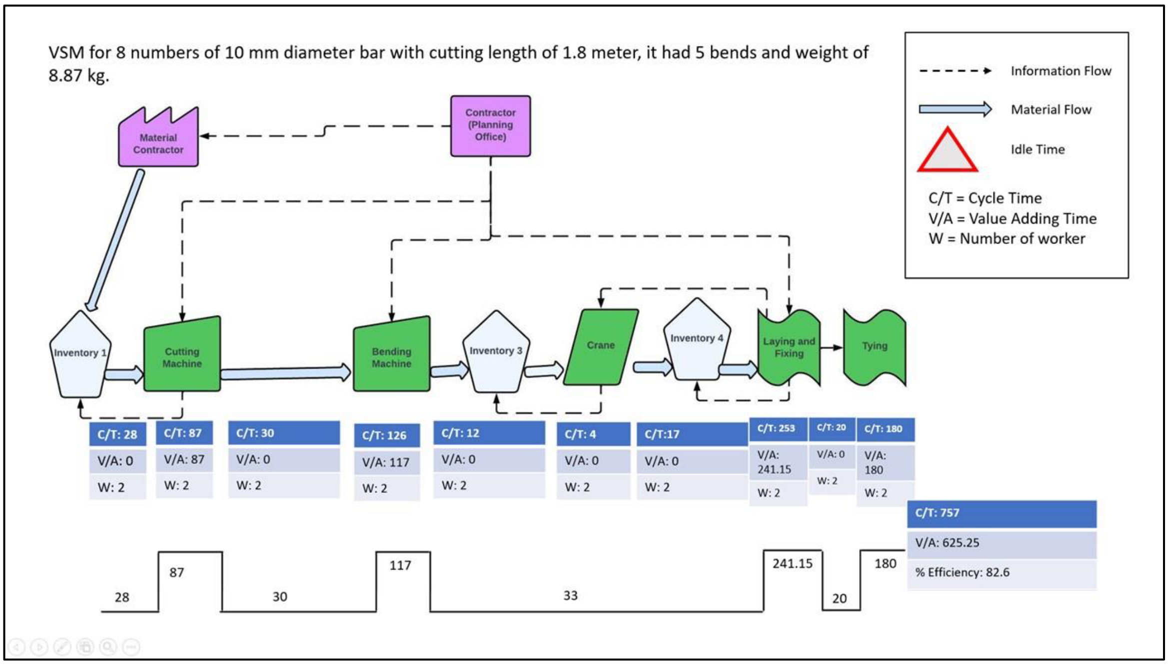

Figure 4: Final State VSM

As was discussed above, it is proposed to remove inventory 2, which is there between the cutting and bending sub-activity. It reduced the time between these sub-activities by 64%, and it also reduced one worker that was shifting the material to inventory. The overall efficiency of the activity, which was 68.9% in the current state VSM, is now 82.6% in the proposed state VSM after applying the lean principle and using the productivity prediction approach.

DISCUSSION

In this study, a labour productivity prediction model is developed using data from a construction site. The model is designed to accurately forecast the absolute labour productivity for upcoming reinforcement activity tasks. Subsequently, the model is utilized to implement lean practices in the activity. The predictions from the model indicate that there is room for improvement, and just-in-time techniques can be implemented by matching the productivity of workstations.

The current state Value Stream Map (VSM) for the activity resulted in a cycle time of 906 seconds. However, when the model's results are used to increase the number of bending workstations relative to cutting workstations, it is possible to reduce inventory and achieve a cycle time of 757 seconds. This demonstrates that utilizing the model can lead to a significant increase of 13.7% in activity productivity. This finding highlights the potential of the labour productivity prediction model in improving construction site efficiency and performance.

CONCLUSION

The construction industry is of labour-intensive nature, and there is a strong need for achieving improvements in the labour productivity aspect. However, the current practice of labour productivity calculation falls short of providing accurate productivity estimates for activity planning, especially when activities are partially completed. To address this gap, this study proposed a novel framework that utilizes the productivity of sub-activities within an activity to predict the absolute productivity of the entire activity.

The proposed framework offers an efficient approach to organizing resources and implementing lean principles, thereby enhancing the overall productivity of the construction project. Through the implementation of the framework, a notable improvement in productivity of 13.7% is demonstrated. It is worth noting that the framework has the potential to further enhance its predictive accuracy by incorporating deep learning algorithms. However, the implementation of such algorithms may require a substantial amount of data sets, making them more suitable for large-scale projects with ample data availability.

In conclusion, the framework presented in this paper addresses the limitations of current labour productivity calculation methods and provides a promising approach for predicting activity productivity in construction projects. The demonstrated improvement in activity productivity highlights the potential of the proposed framework in optimizing labour productivity and promoting the adoption of lean practices in the construction industry. Future research can further explore the integration of advanced algorithms to enhance the accuracy and applicability of the framework and investigate its effectiveness in different construction activities, contexts and project scales.

LIMITATIONS AND FUTURE WORK

The present study exhibits certain constraints which need to be addressed in future research endeavours. Firstly, the study's input parameters are limited in number, thereby failing to account for intangible inputs such as labour fatigue, management practices, and on-site safety factors. The exclusion of these inputs may hinder the accuracy of the prediction model. Thus, their inclusion could potentially enhance the efficacy of the prediction model.

Moreover, the study's prediction model only accounts for absolute productivity during reinforcement activities. However, to employ the model for project planning, it is imperative to consider labour efficiency. Therefore, the model's utility for project planning purposes needs further examination. It is noteworthy that the regression model employed in this study demonstrated satisfactory performance. Nevertheless, the applicability of other deep learning models must be explored for construction activities, especially if the results from the present model are suboptimal.

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AN EVALUATION OF THE LOOKAHEAD PLANNING FUNCTION IN LAST PLANNER® SYSTEM

William Power[1], Derek Sinnott[2], Patrick Lynch[3], and Chris Solorz[4].

ABSTRACT

Last Planner® System (LPS) has been lauded as a critical improvement methodology for project execution. Best results accrue when all functions are utilised. However, in practice, due to lack of knowledge and appreciation of the LPS cycle and complementary interactions required, teams are not achieving optimal outcomes. Effective Lookahead planning that reduces variation and 'making-do' are primary concepts for facilitating better construction task execution.

This study goes 'back to basics' and explores how improved Lookahead planning can enhance project delivery. It utilised a mixed-methods approach with case study design, encompassing interviews, project documentation, and existing research data. The case project utilised Visual Management, Takt concepts, Scrum, and Flow Walks to engage site supervisors proactively and collaboratively in diligent Lookahead planning.

Findings demonstrate involvement of the trades persons in task breakdown and design of the operation ensured better activity and trade flow resulting in improved task execution. Proactive and diligent constraint screening and flow walks resulted in increased constraint identification and better on-time resolution, while also developing a workable backlog. Conducting a First-Run Study resulted in immediate productivity improvement.

The basics of production planning and control are an essential component of Lean Project Delivery. The research highlights the value in practitioners exploring original literature in more depth to gain better knowledge and skills of the Lookahead planning function.

KEYWORDS

Lean construction, Last Planner® System, Lookahead, takt, visual management.

INTRODUCTION & LITERATURE REVIEW

Progressing execution of construction activities is mostly dependent on the completion of other tasks in addition to the timely presence of critical inputs, referred to as the eight flows (Koskela, 2004; Pasquire, 2012). The challenge of coordinating and managing these inputs contribute to issues that frustrate the timely execution of construction projects. Last Planner® System (LPS) is a dedicated tool of Lean Construction (LC) and offers an integrated suite of techniques for

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planning and monitoring task execution on construction projects (Hamzeh et al., 2016). Numerous case studies illustrate performance improvements but there are still implementations that are incomplete or fail to meet objectives, primarily due to difficulties with interpretation of LPS (Ebbs and Pasquire, 2018) allied to its ineffective implementation (Bellaver et al., 2022). Several studies (Daniel et al., 2017; Power and Taylor, 2019) argue LPS implementation varies, and its interpretation is inconsistent. Ballard and Tommelein (2021) sought to address such variation, emphasising the importance of using all functions to ensure planning and execution of tasks are linked to project milestones (Hamzeh *et al.* 2009; Ballard and Tommelein, 2016). A consistent and standard approach is essential as LPS is a series of interconnected functions and best results accrue when all functions are utilised. However, there is a paucity of literature that shows practitioners 'how to do' Lookahead planning and this served as a principal motivation for this research.

This study examines Lookahead planning and shows how the function was enhanced by introducing aspects of Takt planning, Scrum, and Visual Management. Literature and practice gaps suggest there is a need to improve trade involvement in assisting more rigorous and consistent Lookahead planning implementation. Two research questions are posed: 1) How consistent is Lookahead planning implemented in the case company's projects, and 2) What are the effects of the improvement measures implemented on the case company's projects?

The components of LPS include master / milestone schedule, phase / pull planning, Lookahead and make-ready process, commitment / weekly work planning, daily huddles / coordination, and learning and action (Ebbs and Pasquire, 2019). Lookahead planning has been highlighted as an essential step in shielding crews from undertaking tasks that are deficient in inputs, thereby ensuring crews only work on activities that are ready to be executed (Koskela, 2004). Lookahead planning is a first step in production control and links front-end planning with production by connecting the phase / pull planning function with weekly and daily planning by screening all committed tasks and effectively 'making work ready' to be completed (Hamzeh et al., 2012; Bellaver et al., 2022). Ballard (2003) posits Lookahead planning: (1) shapes the sequence and rate of workflow, (2) links master and phase schedules to weekly work plans, (3) shields downstream tasks from uncertainty in upstream tasks, (4) sizes workflow to match capacity and constraints, and (5) produces a backlog of workable activities by screening and pulling. Production is 'made ready' and is given the best opportunity of uninterrupted flow by removing constraints, sizing capacity to workflow, producing a backlog of workable activities, and designing how operations are performed (Ballard et al., 2007). These objectives are accomplished through three main steps (Hamzeh et al., 2008):

- Breaking down tasks into the level of processes then to the level of operations.
- Identifying and removing constraints to make tasks ready for execution.
- Designing operations through First Run Studies.

WORK STRUCTURING

A key element of Lookahead planning is the concept of work structuring, which concentrates on both designing and executing the construction production system. Work structuring can be defined as developing product design (the facility) in parallel with process design (schedules, delivery methodology), organising supply chains, allocating resources, and designing offsite preassemblies to produce reliable workflow and maximise value to both customer and site crews (Ballard et al., 2001; Tsao et al., 2004). This process should span across all project development phases, from definition through design, supply, and assembly (Ballard et al., 2009).

In a construction project, Bertelsen et al. (2007) asserted production flow is optimised when all flows required to complete a task are present at the right time and in the correct amounts for efficient task execution. In addition, Garcia-Lopez et al. (2019) suggest there are two work structuring methodologies: LPS, which has been advanced by other Lean construction researchers (Ballard et al., 2001; Hamzeh et al., 2008), and Takt planning (Frandson et al., 2013; Tommelein, 2017). According to Tsao et al. (2004), LPS work structuring methodology focuses on activity definition, sequencing, and assignment:

- breaking down work into units that can be assigned to specialists (activity definition).
- sequencing activities.
- understanding how work will be handed off between specialists.
- understanding whether work will be executed continuously between locations.
- placing and sizing decoupling buffers.
- scheduling activities (Tsao et al., 2004).

Activity breakdown occurs in conjunction with defining operations, optimising sequencing, coordination of tasks among project stakeholders, resource loading operations, sizing tasks to match available capacity, and analysing tasks for soundness so that all prerequisite inputs are in place (Hamzeh et al., 2008).

CONSTRAINTS

Identification and removal of constraints is the core process for producing dependable workplans and is conducted within a 4-to-12-week planning window (Hammerski, 2021). Constraints should be identified as early as possible in the project (Ebbs and Pasquire, 2018) and can be resolved as late as when tasks are being committed to the weekly work plan. As Hammerski et al. (2021) noted, constraint removal can become a prolonged process as removing a primary constraint can then expose other upstream constraints. Therefore, having a backlog of constraint-free activities is an essential element of Lookahead planning and provides work for crews which can restrict improvisation or 'making-do' (Koskela, 2004).

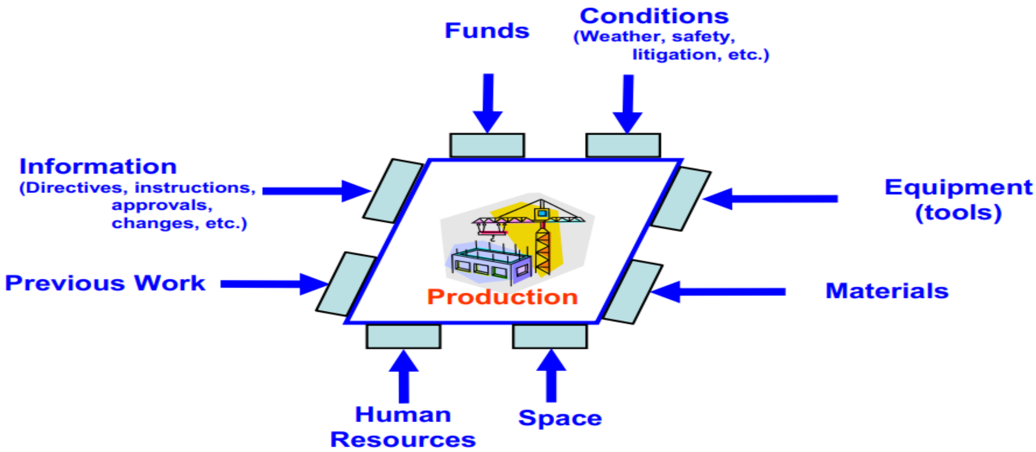


Figure 1: Shielding production from the effects of uncertainty in inputs (Hamzeh et al., 2008).

When an activity starts without having all its prerequisites ready (an incomplete kit), a 'making-do' waste is generated leading to reduced crew productivity (Ronen, 1992; Koskela, 2004). Therefore, a key role of Lookahead planning is to shield production from the adverse effects of uncertainty in inputs as illustrated in figure 1.

FIRST RUN STUDIES

Design and testing of operations should be advanced during Lookahead planning and at least three weeks ahead of execution, according to Hamzeh (2009). A first run study (FRS) is primarily a trial or test run of an operation to evaluate and improve the techniques and methodologies necessary to execute that operation. Potential processes requiring a FRS are those that are new, critical, or repetitive (Hamzeh et al., 2008). Ideally, a FRS should become a standardised element of planning, conducted three to six weeks in advance of a new set of tasks to be executed. A FRS requires the operation to be executed as it normally would by the crew; observations or recordings will seek to improve the process and ensure it interacts effectively with other processes (Howell et al., 1993). By agreeing an effective way to do the work and by setting an achievable standard, a measurement system is then in place on which to assess performance. Standards are an essential part of any process which allows learning and improvement as any movement from the agreed standard can be assessed and examined (Ballard et al., 2007).

PURPOSES OF VISUAL MANAGEMENT

Greif (1991) describes Visual Management (VM) as the use of visual information to enable those that are undertaking work to immediately transfer that information to assist execute the task. The principal objective of VM is to allow production systems learning and improvement while enhancing communication across teams and organisations by increasing process visibility and transparency (Tezel et al. 2016). VM also contributes to the reduction of variability and the elimination of non-value-adding activities (Koskela et al., 2018), as well as to continuous improvement, and incorporates foundational Lean principles. Koskela et al. (2018) suggest VM facilitates faster and more consistent and reliable communication; this contributes to shorter cycle time and less variability. Collaborative planning boards and pull planning exercises facilitate development of a common understanding of different trades inputs, helping to better structure the project planning process. When effectively implemented, VM practices break down complexity by sharing relevant information on-time and by removing information barriers in the work environment (Valente et al. 2019). Systematic and standardised implementation of VM establishes a visual workplace where different objectives of VM can be communicated (Tezel et al., 2016).

Grönvall et al. (2021) suggest the positive effects of takt control and continuous improvement can be enhanced with the adoption of VM tools. Continuous production flow, enabled by increased use and understanding of VM, results from benefits in transparency, discipline, management by facts, simplification and unification, and the creation of shared ownership (Tezel et al., 2016). VM tools are a critical aspect of takt production communication as takt production plans themselves are visually more understandable than traditional schedules.

TAKT PLANNING

In construction, Takt time is a design parameter for labour-paced flow of work (Frandson et al., 2013). A key aspect of takt time planning is to bring more stability to the production process by pro-actively designing continuous workflow for trade activities wherever possible. LPS then provides the control mechanism and stability of the production system. Construction can utilise Takt time as a work structuring methodology to align the production rates of trades by pacing work sequentially through planned zones creating continuous workflow, reliable handoffs, and an opportunity to continuously improve the production system (Frandson et al., 2013). Takt time regards 'space' as a resource to be considered when planning construction projects and designing production operations. Another critical consideration is, in construction workers move around the work as opposed to the work moving to the worker, for example, through an assembly line. Frandson et al. (2013) suggests the difference between Takt time planning and other location-based planning methods is the balance between 'work waiting on workers' and 'workers waiting on work.'

SCRUM

Scrum is a flexible, adaptable, empirical, productive, and iterative method that uses the ideas of industrial process control theory for the development of software systems (Sanchez and Nagi, 2001). Its theory is founded on empiricism and Lean thinking (Engineer-Manriquez, 2021) and is built on three pillars of transparency, inspection, and adaptation. A key characteristic is the autonomous team which is empowered to make relevant decisions to achieve its goals. Work is carried out in time-boxed 'sprints' that empower teams to examine progress and adjust if required, thus minimising risk of miscommunication or over-processing of tasks. In the context of design and construction, Scrum is a framework applicable to project work planning through to deliverable completion. The deliverable could be a calculation, a design, a drawing, an element of a physical task, or a component of a structure.

FLOW WALK

Ebbs and Pasquire (2018, p.736) proposed a 'Flow Walk' to '…firstly identify project constraints at milestone level planning and secondly, to provide the context for desirable action to remove constraints within the framework of the Last Planner® System at Milestone, Phase and Make Ready Planning'. The 'Flow Walk' was used as a structured approach to collaboratively identify constraints and incorporate them into the risk registers and Make Ready Planning. The 'Flow Walk' effectively validates the assignment screening process and replicates Pull Planning conversations at the point of work execution. A common and shared understanding of 'done' and required conditions of satisfaction are direct benefits of the approach (Ebbs and Pasquire, 2018).

RESEARCH DESIGN

The paper reports on an in-depth case study of an EPCMV consultancy implementing LPS and specifically examines the Lookahead planning function. The case project is in Ireland and involved the decommissioning of a pharmaceutical facility and the site's return to an environmentally protected zone to be used as the local community's public space. The critical phases of the project are Clean to Shell, Demolition, Site Remediation, and Groundwater treatment and monitoring. Power et al. (2021) presented an LPS Implementation Health Check (IHC) to highlight the critical components of the functions of LPS and allow project teams to check whether each is being utilised effectively. This study builds on the initial primary research from the IHC paper and then utilises 18 months of new IHC data to specifically examine inconsistencies in Lookahead planning implementation within the case company. This qualitative study utilises a mixed methods approach with case study design (Yin, 2009). Unique sources were purposely sought to increase validity and to provide a wider research perspective, as advocated by Yin (2009) and Stake (1995). The interviews were transcribed and then analysed using a thematic analysis approach, as suggested by Braun and Clarke (2006).

The data was organised into different themes (Braun and Clarke 2006); inferences drawn from the emerging themes were checked by triangulation against the literature review findings and against other sources to check their reliability and integrity. One of the authors was embedded as a Last Planner Facilitator / Lean Mentor on the case project. An action research approach (Eden and Huxham, 1996) was taken on the implementation so the effectiveness of any interventions could be clearly monitored and measured.

Primary data from Power et al. (2021) was examined which investigated 12 projects that utilised LPS to assess effectiveness of implementation of all LPS functions. The projects were measured for compliance with the five core functions of LPS: Milestone Scheduling, Phase Planning, Lookahead Planning, Commitment Planning, and Learning (Ballard and Tommelein, 2016). The implementations were scored on a range from 0 to 5 with: 0 = 'no existence of the function', 3 = 'Partial existence of the function', and 5 = 'Full existence of the function'. Table 1 presents the sources for this paper's research.

Table 1: Research Sequence and Source

Source	Project and Participants
Power et al. (2021) primary research.	12 case company LPS project data from 2017 – 2020. Assessed & analysed implementation of all LPS functions across 12 projects. (n=12)
IHC Data; Case project LPS data.	86 Implementation Health Checks from 6 projects; PPC, reasons for non-completion of tasks, & constraints data from the single case project.
Purposeful Interviews	Interviews with 1 X Client Project Manager, 2 X Construction Manager, 2 X Contractor Site Manager, & 1 X Last Planner Facilitator. All from different projects. (n=6)

For this study, 86 IHC from six projects from June 2021 to December 2022 were examined for alignment with the Lookahead planning function of LPS. LPS data from the single case project was also examined with specific focus on the constraints analysis and resolution data. Semi-structured purposeful interviews were conducted with six interviewees across six projects which implemented the IHC to elicit views on Lookahead Planning. Table 2 presents the interviewees profile.

Table 2: Interviewees profile.

Interviewee	Role	Experience in construction & with LPS
1	Client Project Manager	28 years; 2 years.
2	Construction Manager 'A'	16 years; 6 years.
3	Construction Manager 'B'	9 years; 2 years.
4	Civils Contractor Site Manager	22 years; 2 years.
5	Electrical Contractor Site Manager	11 years; 1 year.
6	Last Planner Facilitator	17 years; 11 years.

Findings were collated and countermeasures proposed which were then piloted on a single case project. Mason (2002) suggests a major challenge for interpretive approaches revolves around how researchers can be sure that they are not inventing data or misrepresenting perspectives. As with any research, this study has limitations pertaining to the small survey size within a single organisation, lack of generalisability, and minimisation and elimination of bias during data collection and analysis stages. Limitations exist due to the research being conducted within a single organisation. Generalisability is not the main concern of this study and Yin (1993) argued that the relative size of the sample "…whether 2, 10, or 100 cases are used, does not transform a multiple case into a macroscopic study", thus, asserting a single case is considered acceptable once it meets research objectives. Bias was mitigated by two researchers being distanced from the project and unconnected with the case company.

FINDINGS AND DISCUSSION

RESEARCH QUESTION 1: HOW CONSISTENT IS LOOKAHEAD PLANNING IMPLEMENTED IN THE CASE COMPANY'S PROJECTS?

Power et al. (2021, p.690) found haphazard and inconsistent LPS implementation across the case company's projects. That study was examining consistent use of all functions and by extension, this study seeks consistency of approach towards implementing Lookahead planning. The summarised findings from 12 selected projects that implemented LPS from 2017 to 2020 were evaluated by Power et al. (2021) and results are presented in table 3.

Table 3 indicates difficulties with understanding the importance of consistent implementation of all functions of LPS. While the Learning and Phase planning functions were poorest used functions, Milestone and Commitment planning were most used. Lookahead planning, considered so critical in the literature, scored 55%; this pointed to inconsistent use of the complementary functions of LPS. Following from this Power et al. (2021) finding, the next step was to examine how the Lookahead planning function implementation could be improved.

Table 3: Status of LPS implementation on twelve projects (Power et al. 2021).

Survey Findings Score from 0-5 (0=no, 5=full)	Milestone Planning	Phase Planning	Lookahead Planning	Commitment Planning	Learning
Mean Values	3.7	2.1	2.8	3.7	2.2
Median Values	3.5	2	2.5	4	2
Lowest Values	2	0	2	3	0
% Implementation	73%	42%	55%	73%	43%

The IHC was introduced on projects using LPS in June 2021. By December 2022, 86 IHC are available for examination from six different projects. As the IHC is a system compliance and process improvement tool, its purpose is to reduce non-compliance with the agreed LPS implementation standard. An audit of 86 IHC showed high levels of non-compliance with the Work Structuring and Constraint Management requirements of the Lookahead planning function of LPS. At the time, First Run Studies (FRS) was not incorporated into the IHC. The next step was to conduct interviews with persons knowledgeable on LPS to seek further detail on the Lookahead planning process. Table 4 presents interviewees collated opinions on the Lookahead planning process.

Table 4: Interviewees opinion on Lookahead planning process.

Opinions on Lookahead planning process
"Looking 4 to 6 weeks ahead is too far and is unnecessary as there are more urgent issues to address."
"LPS is taking too much time and Constraint Walks take supervisors away from direct supervision."
"Design should be completed, and it isn't our job to screen their deliverable."
"It shouldn't be the contractor's job to identify what inputs are missing."
"Constraints identification is not taken seriously enough."
"It is difficult to plan off PDFs of Master Schedules."
"Being pushed to start new tasks on a specific date when ongoing tasks are incomplete leads to frustration, especially when the ongoing task has extra scope added."
"Let us finish what we are at before we move onto a different location."
"Being able to 'see' what needs to be done where, and who is doing it would be helpful."
"Incumbent client contractors need to understand that external contractors have work priced through competitive tenders and therefore the incumbents should get their own tasks complete when they say they will."
"Constraints removal process needs accountability and management."
"Several contractors working in the work area can sometimes slow each other down and lead to safety issues."

Analysis of the comments confirms a distinct lack of awareness and understanding of the LC and LPS ways of working and how that differs from traditional push methodologies. LPS implementation needs to be more than just a tool-focused approach and must bring cultural, and mindset change along the journey as well. Some comments in table 4 point to frustration with the constraints process and indicate any next steps should be holistic in approach and include all stakeholders' interests.

RESEARCH QUESTION 2: WHAT ARE THE EFFECTS OF THE IMPROVEMENT MEASURES IMPLEMENTED ON THE CASE COMPANY'S PROJECTS?

Literature asserts the importance of the Lookahead planning function and the IHC examination findings indicated poor focus and application of the constraints process across the six surveyed projects. Table 4 confirmed this and added further detail. In addition to the constraints process, improved work structuring was required and there was an absence of FRS. The case company has a 'Lean Team' that supports project teams implement process improvements. The Project Director was favourable towards experimentation to improve the Lookahead planning function. This leadership support was a critical first step in implementing changes to the existing processes. Firstly, the team needed to agree on what constituted 'good' Lookahead planning. From the literature it was agreed to focus on Work Structuring, Constraints Management, and First Run Studies. These were further broken down into actionable activities as shown in table 5.

Table 5: Actionable activities to implement Lookahead Planning

Work Structuring	Constraints Management	First Run Studies (FRS)
Break work into defined activities that can be assigned to specialists. Sequence activities by logic and flow. Make explicit how work will be handed off between specialists by involving the 'next-customer.' Visualise the Pull / Phase Plan to understand continuous workflow. Position, size, and make visible decoupling buffers. Schedule activities to prioritise release of value-adding work to progress the project. Introduce Takt concepts to structure task, trade, & inputs flow.	Seek to identify constraints at every opportunity. Ensure primary constraints are broken down to permit recursive examination of sub-constraints. Establish clear ownership and accountability. Make the 8-flows visible to all. Keep building a constraint-free backlog that is available for all crews. Visualise location-based constraints. Introduce Scrum framework to ensure daily focus on constraints removal.	Introduce the concept of FRS to encourage studying an activity with the objective of standardising the work and removing any non-value adding steps. Video record where possible to review several cycles of an activity to seek improvements. Create an environment where new ideas can easily surface and be tested. Focus on enhancing persons jobs, welfare, and working conditions through improving safety, quality, and logistics. Adopt a quality focus on handoffs to ensure no defects are passed on.

Work Structuring - The primary change implemented with work structuring was the involvement of the trades persons in breaking down the tasks into finer detail and then building the operation to ensure activity and trade flow through the buildings. A sticky-note example of a work structuring exercise was conducted with the work crew supervisors. Firstly, all tasks required to 'clean' a building were written on sticky notes (dedicated colour per trade) and put on the board. Next, each task was ordered in sequence to generate an Overall Process Analysis

(OPA). Durations were assigned to the OPA for a specific building, and this was then tested in the field. Once durations were validated the OPA could be extended into a visual that incorporated all areas in the selected Lookahead window. In addition to the OPA sticky note visual, a 6-week Lookahead was applied onto the site layout plan (figure 2); crew supervisors could then view which locations were coming into the near-term planning horizon.

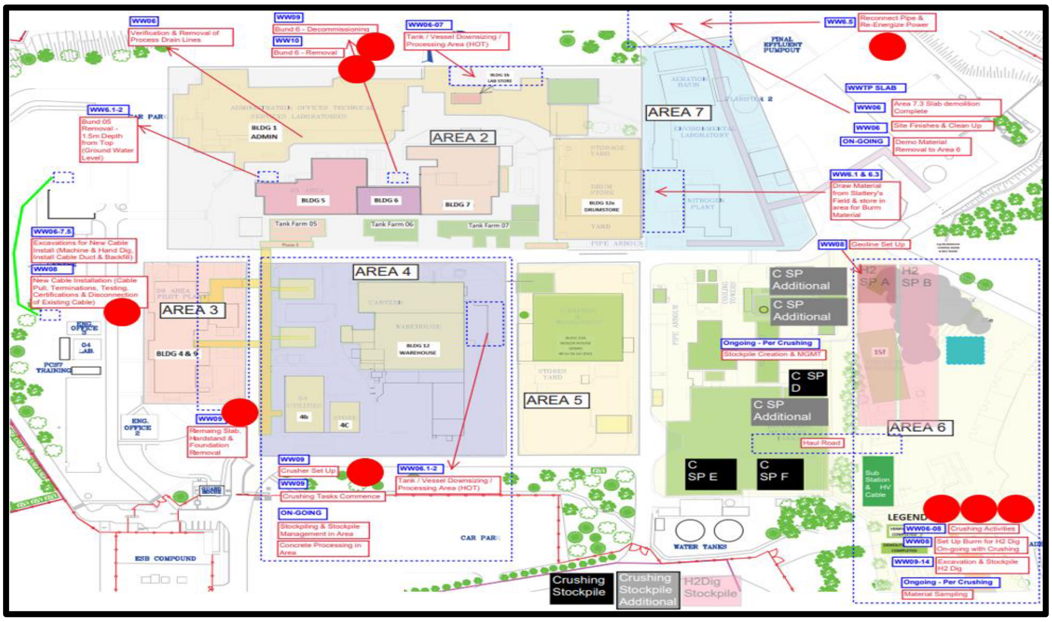
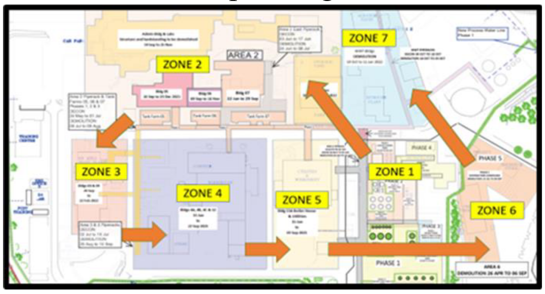


Figure 2: 6-week Lookahead / site layout plan.

Takt concepts of moving through zones in sequence, balancing work package sizing, and matching crew and plant capacity with planned work durations were implemented in the earthwork remediation phase. Visualisation of the planned progression through the zones (figure 3) and its positioning on the site information board shared the high-level plan with the entire team. Incorporating both Takt and VM concepts assisted planning work structuring.



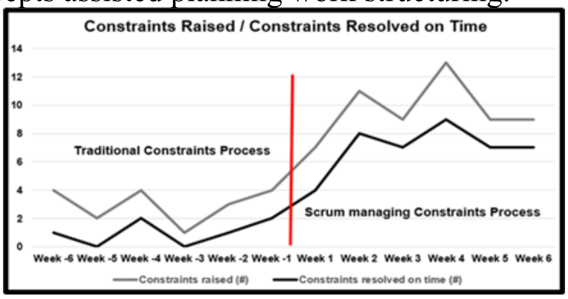
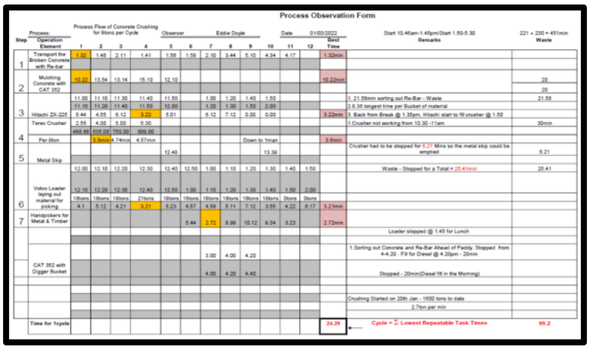


Figure 3: High-level work-flow visualization. Figure 4: Improved constraints process.

Constraints Management - Constraint screening occurred at every opportunity and red dots as suggested by Ebbs and Pasquire (2018) were positioned at each location where an unresolved constraint existed (figure 2). Constraints were managed on a virtual board (Trello) using the Scrum framework. A key point was the presence of a dedicated Scrum Master who was managing the constraints resolution process with a committed 'Development Team'. The Construction Manager was the Product Owner, and the entire constraints process was proactively driven. Twice-weekly constraint / flow walks were mandatory on Tuesdays and Thursdays with the distinct objective of identifying any possible risk or concern that might cause delay to a task, a safety issue, or a quality defect. A critical finding was the increase in both constraints raised and constraints resolved on-time as indicated on figure 4. This was a direct result of the constraint / flow walks and the commitment to the Scrum process for resolving the constraints. A relentless focus was placed on creating a backlog of constraint-free tasks. These were available on each week's weekly work plan should any adverse event impact the planned tasks. A new area of focus was the concept of testing the resolved constraint for quality. Past experienced had shown that incomplete closure of the constraint only led to further delay and frustration as supervisors resorted to improvisation to allow the activity to proceed. It is important for the overall implementation that a quality focus is maintained at all steps in the design, construction, and close-out phases.

First Run Studies – A large stockpile of demolition material was ready to be crushed with the concrete and reinforcement steel to be separated and recycled. It was agreed the specialist contractor would commence the first run of the activity and allow video recording and observation to facilitate process examination and improvement. The activity involved excavator #1 sorting broken concrete from earth and creating a spoil heap for excavator #2 to feed the crusher. Crusher output from 1100hrs to 1400hrs was averaging 100 tonnes per hour. The activity was recorded and logged as per figure 5. The Process Observation noted excavator #2 was constantly waiting for material and often had to move around and commence segregating its own clean stockpile. Excavator #1 was on a separate location on the heap and was not communicating with excavator #2. This was discussed with the crew leader and the key point identified was the excavators were not working together as a team and coordinating their movements. The supervisor spoke with both drivers, and they then began to work together in more coordinated action as shown in figure 6. This change increased crusher output from previous average of 100 tonne per hour to 146.4 tonne per hour from 1500hrs to 1600hrs on that day. On subsequent days production was consistently more than 135 tonne per hour.



Process Observation Form

Process: Process Flow of Concrete Crushing for 9tons per Cycle — Observer: Eddie Doyle — Date: 01/03/2022 — Start 10.45am-1.45pm/Start 1.50-5.30 — 221 + 230 = 451min

Step	Operation Element	1	2	3	4	5	6	7	8	9	10	11	12	Best Time	Remarks	Waste
1	Transport the Broken Concrete with Re-bar	1.32	1.46	2.11	1.41	1.56	1.58	2.10	3.44	5.10	4.34	4.17		1.32min		
2	Mulching Concrete with CAT 352	10.22	13.54	13.14	15.10	12.10								10.22min		20
																20
3	Hitachi ZX-225	11.00	11.10	11.30	11.40	11.50		1.00	1.20	1.40	1.50				1. 21.58min sorting out Re-Bar - Waste	21.58
		11.10	11.20	11.40	11.50	12.00		1.20	1.30	1.50	2.00				2. 8.36 longest time per Bucket of material	
		5.44	4.55	6.12	3.22	5.01		6.12	7.12	0.00	0.00			3.22min	3. Back from Break @ 1.35pm, Hitachi start to fill crusher @ 1.50	
	Terex Crusher	2.55	4.00	5.00	5.30										1.Crusher not working from 10.30 -11am	30min
		488.66	635.00	750.00	809.00											
4	Per 9ton		3.6min	4.74min	4.57min					Down to 1man				3.6min		
5	Metal Skip					12.48					13.39				Crusher had to be stopped for 8.21 Mins so the metal skip could be emptied	8.21
6	Volvo Loader laying out material for picking	12.00	12.10	12.20	12.30	12.40	12.50	1.00	1.10	1.20	1.30	1.40	1.50		Waste - Stopped for a Total = 25.41min	25.41
		12.10	12.20	12.30	12.40	12.50	1.00	1.10	1.20	1.30	1.40	1.50	2.00			
		18tons	18tons	18tons	21tons	18tons	18tons	18tons	18tons	18tons	18tons	0tons	0tons			
		4.1	5.12	4.21	3.21	5.23	4.57	4.58	5.11	7.12	3.55	4.22	6.17	3.21min		
7	Handpickers for Metal & Timber						5.44	2.72	8.99	10.12	9.34	3.23		2.72min		
															Loader stopped @ 1.45 for Lunch	
	CAT 352 with Digger Bucket							3.00	4.00	4.20					1.Sorting out Concrete and Re-Bar Ahead of Paddy. Stopped from 4-4.20 . Fill for Diesel @ 4.20pm - 20min	
								4.00	4.20	4.40					Stopped - 20min(Diesel fill in the Morning)	
															Crushing Started on 20th Jan - 1600 tons to date	
															2.7ton per min	
	Time for 1cycle													24.29	Cycle = Σ Lowest Repeatable Task Times	95.2

Figure 5: FRS Process Observation exercise.

Figure 6: Excavators working as a team.

CONCLUSION AND RECOMMENDATIONS

The research shows that the basics of production planning and control are an essential component of construction delivery and posit practitioners revisit original literature to gain better knowledge and skills of the Lookahead planning function. Improving input flows to reduce variation and 'making-do' are primary concepts for improving construction task execution. Consideration of the three primary aspects of Lookahead planning, namely Work Structuring, Constraints, and First Run Studies should be fundamental to LPS implementation.

Involving the wider management team and trades in the work structuring exercise creates a common and shared understanding of the challenges and peculiarities of the project. Diligence around screening of tasks, constraints identification, their prioritisation, and effective resolution contributes to smooth workflow as well as enhancing enthusiasm and engagement amongst the team. Creating an environment where First Run Studies are encouraged and financially supported leads to less disruption and increased productivity during the project.

Previous studies have shown how the Lookahead planning function can be advanced with metrics and digitisation. However, to ensure we do not digitise a poor process we must make certain Lookahead planning is structured in accordance with the basics of production planning and control. The effective use of Visual Management, Takt concepts, and the Scrum framework can complement Lookahead planning, task make ready, and ensure better project execution.

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A STUDY OF THE BENEFITS OF LEAN CONSTRUCTION DURING THE PANDEMIC: THE CASE OF PERU

Andrews A. Erazo-Rondinel[1], Isaac M. Ccoyllar[2], Anabela Huaccha[3], and Godofredo Barrantes[4]

ABSTRACT

Lean Construction (LC) has been implemented worldwide in different construction projects, and the Covid-19 pandemic has been no exception. However, more research needs to be compiled on the benefits of LC during this period, considering the high variability and uncertainty generated. Therefore, this article evaluates the benefits of implementing LC during the pandemic stage. In the first stage, a literature review was conducted using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), where the main benefits of implementing Lean Construction during the pandemic are identified. In the second stage, the benefits were validated through interviews with professionals in different Peruvian construction projects. The main benefits were: improved planning, easier identification of constraints, and improved project communication. The following study will help construction industry professionals consider LC implementation's benefits in future scenarios with high variability.

KEYWORDS

Lean Construction, Covid, pandemic, benefits, Peru

INTRODUCTION

The construction sector is one of the sectors that promote higher economic growth worldwide. However, it faces several problems, such as low productivity (Barbosa et al., 2017) and; a fragmented chain (Hossain & Nadeem, 2019); it is also a dangerous industry, where personnel are exposed to numerous safety risks, resulting in deaths or serious injuries (Lee et al., 2014). These problems have been heightened in the wake of the COVID-19 pandemic, where the construction sector faced various impacts such as reduced productivity, delayed project delivery, cost overruns (Ahmed et al., 2022), labor shortages (Husein et al., 2021), among others.

Many of the problems described above have been solved through the application of LC; several authors have recorded benefits such as reduced variability (Alarcón et al., 2008), mitigation of cost overruns and delay in project delivery (Gómez-Cabrera et al., 2020). So also during the pandemic, LC has been implemented, achieving benefits such as improved planning

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(De la Torre et al., 2021), improved workplace safety, reduction in the number of contagions (Verán & Brioso,2021), maintaining social distance between workers (Santos et al., 2022).

Despite the benefits shown during the pandemic, little research has compiled the benefits obtained from LC. Therefore, the main objective of this study is to identify the main benefits of implementing LC in the Peruvian construction industry during Covid-19. The construction sector in developing countries was hardest hit by Covid-19 (Al-Mhdawi et al., 2023). In Peru, the construction sector was one of the sectors most affected by the onset of the Covid-19 pandemic since the Peruvian government declared a state of emergency in the country, paralyzing all activities in the construction sector (Instituto Peruano de Economía, 2020), which caused the construction sector to suffer a reduction in GDP of -30% per year (Madera et al., 2022). In addition, the Peruvian government proposed a series of guidelines for the spread of Covid-19, such as evaluating the outbreak (control of body temperature and pulse oximetry, and identification of symptoms), installing information panels, maintaining a distance of 1.5 meters, providing hygiene products, ensuring the use of masks, using personal protective equipment, and daily cleaning and disinfection of the entire construction site and equipment (MINSA, 2020), which affected the construction work (Verán-Leigh & Brioso, 2021).

The article begins with a literature review identifying the main benefits associated with LC during the pandemic. After that, six Peruvian professionals were interviewed to compile the benefits they obtained with the implementation of LC and validate them with respect to the benefits obtained from the literature review.

BACKGROUND

COVID IMPACTS IN CONSTRUCTION PROJECTS

The Covid 19 pandemic has affected the whole world, especially in the construction sector (Rani et al., 2022), so several studies have been conducted to understand the impact in different parts of the world. For example, Al-Mhdawi et al. (2021) studied the impacts in Iraq, where the significant impacts were supply chain disruptions, labor restrictions, and legislative changes. In South Asia, research was conducted in India, where, according to Rani et al., 2022, the three main impacts were labor shortages, supply chain disruptions, and decreased productivity in Construction. In Latin America, studies have also been recorded; for example, according to Araya and Sierra, 2021, based on data from 40 interviewees, in Chile, impacts on productivity, technical performance of workers, and present and future financial solvency were obtained, such impacts were the ones that caused the most effects on the stakeholders who addressed the construction project. These impacts are mentioned following the impacts found in the United States; according to Alsharef et al. (2021), among the impacts found are reductions in efficiency and productivity rates, material delivery delays and material shortages, and the suspension or slowdown of construction projects. Finally, in the case of Peru, according to Fernandez et al. (2021), the impact was evidenced by a significant increase in labor costs.

LEAN CONSTRUCTION BENEFITS

Lean Construction has been implemented in different countries, such as, for example, Egypt, where Shaqour (2022) mentioned that the main benefits are improved process control, improved planning, reduced project execution time, and improved safety. Similarly, Sarhan et al. (2017) evaluate the benefits in Saudi Arabia. He identifies similar benefits to Shaqour's (2022) study, such as reduction of construction time and process improvement, and mentions that quality improvement is the main benefit of the Saudi Arabian industry. Finally, in the case of Peru, Erazo-Rondinel and Huamán-Orosco (2021); identified the main benefits of improving on-site planning; identifying waste and minimizing it; and reducing construction time.

RESEARCH METHOD

The following research follows two stages; in the first stage, a literature review is conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. In the second stage, a qualitative study is conducted through 06 interviews with professionals about their experience implementing Lean Construction during the pandemic. Each of the stages is described below (Figure 1).

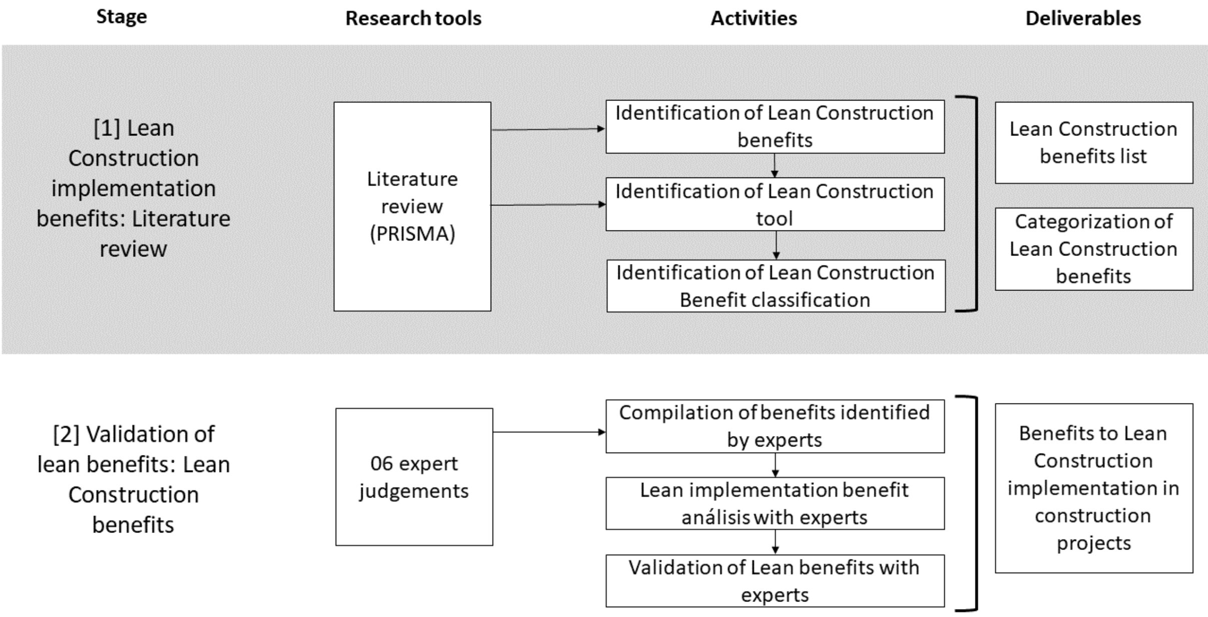

Figure 1: Diagram with the main stages of the investigation.

FIRST STAGE: PRISMA REVIEW

A systematic literature review was performed to identify, select, and include the articles to be evaluated in this study, following each step of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology (Mamani et al., 2022). PRISMA has been used in studies associated with Lean (Besser et al.,2017; Souza et al.,2021).

For the literature review, a search of publications related to Lean Construction and Covid was conducted using Scopus and the IGLC database. Scopus is one of the databases with a vast domain in construction research compared to other databases (Galaz-Delgado et al., 2021). In addition, the IGLC database was used, which hosts most publications on the application of Lean Construction worldwide (Daniel et al., 2015). In the first stage, the search was performed using keywords, as shown below. For the SCOPUS database, they were I ("lean construction" AND "covid"), II ("lean construction" AND "pandemic"), and III ("lean construction" AND "coronavirus") and for the IGLC database, they were a) coronavirus, b) covid and c) pandemic.

A filter of publications ranging from 2020 to 2023 was applied, which had 85 articles and included four by collecting snowballs that could contribute to the study/evaluation of the benefits of Lean Construction, having a total of 89 articles. For the next eligibility phase, 48 duplicate publications were eliminated from the reviewed articles after having combinations I, II, and III. Next, relevant articles were filtered for evaluation, considering that they refer to the benefits, impact, or applications of lean tools during the Covid-19 pandemic. In total, 22 articles were excluded through a title and abstract review, leaving a total of 19 articles, which were filtered again through a complete review, thus excluding six articles that did not meet the criteria to be considered in this study, leaving a total of 13 articles that were considered for this research. The above steps are described in Figure 2.

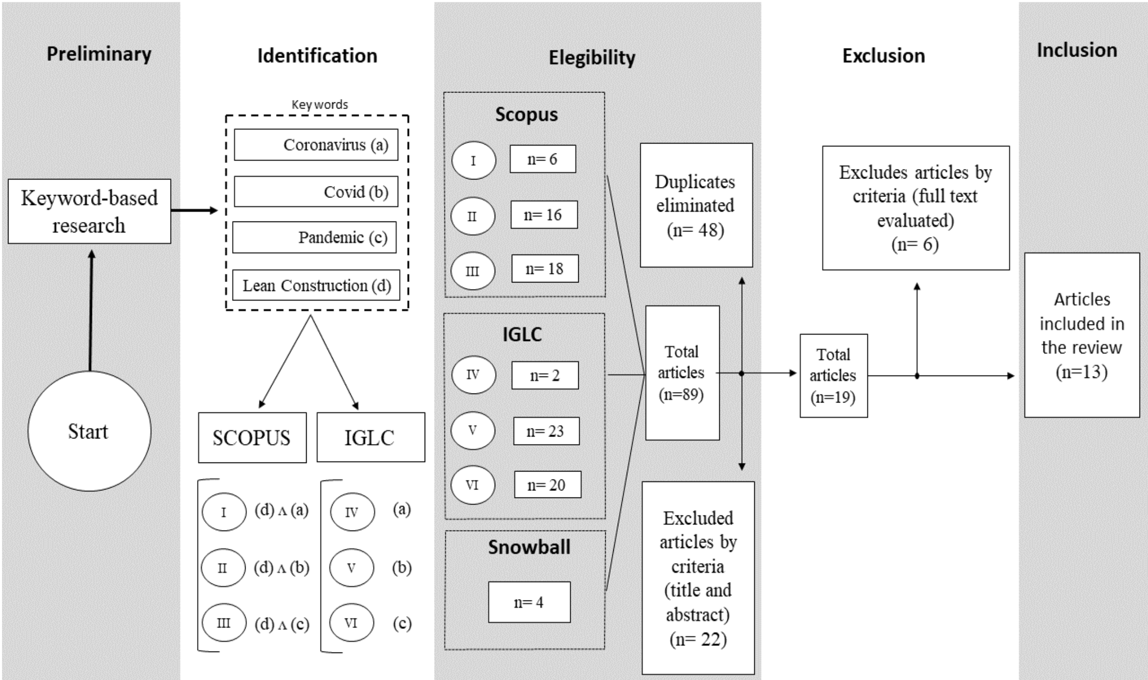

Figure 2: PRISMA flow diagram for the systematic review.

After the literature review, we will continue with the second stage corresponding to the research's qualitative approach.

SECOND STAGE: QUALITATIVE STUDY

The qualitative approach has been previously used with topics related to Lean Construction, for example, to identify the significant impacts and difficulties of LPS in Brazilian companies (Viana et al., 2010), to identify tools and facilitators for lean adoption (Bashir et al. 2013 and Marhani et al. 2018). That is why the following study, like those mentioned, is based on a qualitative analysis of the benefits of Lean Construction during the pandemic context.

For this stage, 6 participants were selected from various construction projects in Peru who applied Lean during the pandemic; below is a description of the profile of the interviewees and the type of project in which they participated (Table 1). The interviewees were asked to have at least five years of experience implementing the Lean philosophy. The interviews were conducted by telephone and video calls and lasted 20 to 30 minutes with each interviewee. The interview was divided into two stages: a first stage where the interviewee's information was collected, such as years of experience, experience in implementing Lean Construction, and types of projects in which he/she has participated. In the second stage, the benefits obtained in the literature were validated. The experts were asked if they had observed the benefit, and they were asked to give examples. Concerning the limitations, the study includes using a convenience sample and a small sample size because six professionals were interviewed. In addition, the benefits obtained will vary according to the region where they were applied since government measures about COVID vary.

Table 1: Profile of interviewees

Number	Years of experience	Years of exp. With LC	Current role	Projects participated in
Interviewee 1	7 years	7 years	Risk leader	Infrastructure, Urban development, mining, plants, the aviation sector
Interviewee 2	12 years	12 years	Manager	High-rise buildings and retail projects
Interviewee 3	15 years	7 years	Operations Manager	High-rise buildings
Interviewee 4	7 years	7 years	Technical Office Engineer	High-rise buildings and sports infrastructure
Interviewee 5	17 years	12 years	Superintendent	High-rise buildings
Interviewee 6	5 years	5 years	Fire Water Subcontractor	High-rise buildings

RESULTS AND DISCUSSION

RESULTS OF LITERATURE REVIEW

Main Lean Benefits

Another result of the literature review was the identification of benefits. Thus, 11 main benefits were identified from the 13 articles mentioned. The benefits are arranged in Table N°2. Among the benefits, the following were identified: Improved planning ("B1"), Facilitation of constraint identification ("B2"), Improved productivity in the COVID stage ("B3"), Alternatives for activity sequencing ("B4"), Improved decision making in the project ("B5"), Maintaining social distancing ("B6"), Improving safety at the work site ("B7"), Reducing the number of contagions ("B8"), Transparency with project information ("B9"), Improving communication in the project ("B10"), Continuous improvement of the project ("B11").

From Table N°2, we can notice that the main benefit obtained by the authors is the improvement of planning through the reduction of variability (9 results) because most authors have implemented LPS. The second benefit identified is the timely identification of constraints (6 results) because the Covid-19 context is a context of high uncertainty, and the team, using lean tools, can better protect its planning. Another benefit obtained is the improvement of productivity (with five results). In this case, the authors have mentioned that the use of LC helps mitigate the effects of the pandemic on the project's productivity. In addition, other results obtained have reduced the number of contagions and improved safety at the work site because they are mainly related to better project planning and adequate distribution of the crews.

Table 2: Lean benefits in relation to the selected articles.

Autor	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	Total
McHugh et al.2021	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**				**8**
Espinoza et al.2021					**x**							**1**
Verán & Brioso.2021	**x**	**x**		**x**				**x**				**4**
Santos et al.2022		**x**		**x**		**x**						**3**
Chaize et al.2022					**x**				**x**	**x**		**3**
Sosa & De La Torre.2021					**x**				**x**	**x**		**3**
De La Torre et al.2021	**x**	**x**	**x**									**3**
Le & Nguyen.2022	x											1
Jiang et al.2022	x		x				x					3
Parameswaran & Ranadewa.2021	x		x								x	3
Salazar et al.202	x	x										2
Retamal et al.2021	x	x				x						3
Simeão & Ferreira.2022	x		x	x							x	4
Total	9	6	5	4	4	3	2	2	2	2	2	

RESULTS OF INTERVIEWS IN PERUVIAN CONSTRUCTION PROJECTS

Likewise, the benefits obtained by the interviewees are related to the list of benefits obtained in the literature review, which we can evidence in Table N°3 that the most frequent benefit by the interviewees at the time of using Lean Construction was benefit B1(Improvement of planning) taking into account that each of the interviewees applied in the six construction projects the LPS tool for example, interviewee 01 mentioned ["*Level 4 schedules were developed to support the master schedule and it was beneficial to consider the restrictions we had with the Covid problem*"]. Regarding the relation of items obtained from the literature review, benefit B1 has a frequency of 9 answers, a similar frequency also happens with B2 (Facilitation of constraint identification) being the second most demanded, with a total of 6 answers.

In contrast to the literature review, benefit B3 (Improved productivity) and benefit B6 (Maintaining social distance) was not very common among the interviewees, as they indicated ["*Due to social distance some activities saw their productivity reduced"]* and *["They only followed legal norms*"], and in comparison with the items obtained from the literature review, they had a total of 5 and 3 mentions in favor, respectively.

We highlight benefit B4 (Alternatives for the sequencing of activities) by the six mentions by the interviewees. With B4, the time has been optimized by flexibly changing schedules, having an objective as a goal, and concerning B5 (Improvement of decision making in the project), had a total of 4 according to the answers of the interviewees, for example, according to interviewee 01 ["*It helped in the integrated meetings that were made with the field people*"]. Likewise, in the literature review, both benefits B4, and B5 obtained a total of 4 mentions, which evidences a small variation in the frequency given in B4.

Table 3: Benefits identified by interviewees.

Code	E1	E2	E3	E4	E5	E6
B1	X	X	X	X	X	X
B2	X	X	X	X	X	X
B3						
B4	X	X	X		X	X
B5	X	X			X	
B6		X		X		
B7		X	X		X	
B8		X				
B9	X	X	X	X		X
B10	X	X	X	X		X
B11	X	X		X		X

Of the benefits related to workers' safety, benefit B7 (Improvement of safety in the workplace) and B8 (Reduction in the number of contagions), B7 has a higher frequency than the literary review, also according to interviewees 02, 03, and 05, they mention that ["*The companies implemented order and cleanliness, through the 5S tool*"]. On the other hand, benefit B8 has a better frequency in the literature review and interviews since it is complicated to establish a relationship between lean tools and reducing the number of contagions. However, one of the respondents mentions that ["*Thanks to planning and proper distribution of subcontractors, in 8 months only one member of his team was infected by Covid-19*"]. Therefore, both benefits compared to the article got two mentions.

We see that also the benefits B9 (Transparency with the project information), B10 (Improvement of the communication in the project), and B11 (Continuous improvement of the project) have a high degree of percentage accepted by the interviewees, taking into account that in B9, the Spaghetti diagram was used, for the subject of the approaches, optimizing displacements and that they are the correct ones, in B10, the communication channels were improved to make them more effective. Finally, in B11, the PPC (Percentage of Plan Completed) and CNC (Causes of Non-Compliance) metrics together with a historical database, according to the interviewees mentioned that the above ["*serves to make decisions and corrective options, since it allows you to have more practical and dynamic visual tools*"]. Therefore, in this opportunity, B9, B10, and B11 obtained two mentions of each benefit compared to the article.

CONCLUSIONS

The following research seeks to identify the main benefits of implementing Lean Construction through a literature review and interviews with Peruvian construction professionals. The main benefit obtained was the improvement of planning, associated with identifying constraints and generating alternative plans, all related to the Last Planner System. The second benefit identified was the improvement in the identification of constraints, improved communication, and improved transparency, mainly because the interviewees have been implementing the Last Planner System and promoting weekly meetings. The least observed benefit is the reduction in the number of contagions. The interviewees mentioned that this could not be determined and could be an effect of good lean planning.

Another important conclusion is that the interviewees quickly identified the benefits associated with Lean Construction because they have been implementing LC for over five years, which generates an understanding of the tools and principles. These results could change if professionals with little experience with LC are interviewed.

The authors recommend conducting qualitative studies in other countries since each country implemented different measures concerning Covid-19 and to determine if there could be any relationship between the measures and the benefits of LC.

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INTEGRATING STANDARDIZED WORK AND PRODUCTION STATUS CONTROL TO SUPPORT LOCATION-BASED PLANNING AND CONTROL

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ABSTRACT

Standardized Work (SW) is an approach to standardize and improve the efficiency of operations cycles. SW can support the implementation of Location-Based Planning and Control (LBPC) by balancing workload between workers, synchronizing different processes and allowing early identification of deviations. Digital technologies can support the implementation of SW by providing real-time feedback to support project monitoring, communication, and information management. The aim of this research work is to propose a model that integrates SW and production status control by using existing digital technologies to support LBPC. Design Science Research (DSR) is the methodological approach adopted in this investigation. The study initially focused on the collaborative identification of critical interrelated activities to implement SW. Then the integrated control model of SW and production status was proposed with the support of visual management devices and digital technologies. As a result, it was possible to effectively synchronize and balance the resources of a set of interrelated activities, increasing the stability of those activities. Therefore, the model can be used as a mechanism to manage variability in LBPC and increase the degree of process standardization while having short cycles of feedback to promote continuous improvement.

KEYWORDS

Location-Based Management (LBM), Takt planning (TP), standardization, production status control, digital technologies.

INTRODUCTION

Standardization is a key managerial mechanism to reduce process variability. In construction, standardization is often focused on achieving compliance with standard procedures, based on the traditional idea of finding the best way of performing an activity, with little emphasis on continuous improvement (Saffaro et al., 2008). By contrast, in the Lean Production Philosophy, standardization is focused on the operations performed by workers (Martin & Bell, 2017) and is known as Standardized Work (SW) (LIB, 2003). SW is an action-oriented procedure in which detailed instructions are established for each operator's work in operations cycles (Ohno, 1997).

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These procedures lead to the standardization of operations (Mariz, 2012) and are the basis for continuous improvement (Liker, 2004). Ohno (1997) suggests that there are three necessary elements for SW: (a) takt time – time available for production, based on customer demand (Alvarez & Antunes Jr., 2005); (b) standard sequence of operations – sequence of steps performed by each worker within a cycle time[5] (Monden, 2011); and (c) standard inventory – minimum amount of items needed in the process that allows the operator to work efficiently (Ohno, 1997). In addition, Fireman et al. (2018) pointed out that slack must be defined when designing SW for any activity and that the existing variability of construction operations must be considered.

Takt time has been strongly related to Location-Based Planning and Control (LBPC), which can be defined as a planning and control approach that makes explicit the workflow and the relationship between construction activities, time and work zones (Olivieri et al., 2019). LBPC involves a set of techniques, including the line of balance (LOB), which represents the master plan (Ballard & Tommelein, 2021). The major benefits of the LOB are that several concepts related to the Lean Production Philosophy are explicitly used, such as batch size, work-in-progress, cycle time and rhythm of processes (Schramm et al., 2006).

SW is a collaborative effort aiming to standardize operations cycles to reduce variability, which plays a critical role in the synchronization of processes. Therefore, different crews can achieve similar cycle times by balancing the workload between different workers or teams and aligning them with an established takt time (Mariz, 2012). Although SW is one of the most important aspects of the Lean Production Philosophy, it is still underutilized in the Construction industry (De Bortoli Saggin et al., 2017). In fact, previous works on LBPC have not emphasized the opportunity of using SW to support the synchronization of processes by using collaborative planning meetings (Binninger et al., 2017).

Moreover, the growing complexity of construction projects has demanded the adoption of digital technologies to support project monitoring, communication, and information management (Bryde et al., 2013). Current data collection and monitoring systems depend on on-field personnel, which is time-consuming and error-prone (Golparvar-Fard et al., 2011; Son & Kim, 2010), while people should spend time analysing progress and metrics, detecting deviations and problems early (Fullerton & Wempe, 2009). Therefore, there are opportunities for using digital technologies to improve progress monitoring, by providing real-time feedback on the status of the production system (Kropp et al., 2018) to improve the capacity to respond and adapt to expected and unexpected changes (Hollnagel et al., 2006).

Therefore, alternative and complementary controls to support existing planning and control approaches are needed to deal with the dynamic nature of construction (Hajdasz, 2014). Controlling production status can potentially increase transparency and promote better communication between trades, which, according to Lehtovaara et al. (2021), must be considered in LBPC approaches. Additionally, technology can be used to monitor construction progress and production status, e.g., 360º cameras attached to hard hats connected to data management cloud platforms (Kropp et al., 2018).

Accordingly to Koskela and Howell (2008), job dispatching consists of assigning a task ready for execution to a crew and communicating this assignment as authorization to start work. However, this procedure is generally done by oral communication (Koskela & Howell, 2008). So, there is an opportunity to develop planning and control models that adopt digital technologies to formally assign workers to tasks and workstations, enhance understanding of planned work and increase commitment.

Studies that address SW in construction (De Bortoli Saggin et al., 2017; Mariz, 2012; Tommelein & Emdanat, 2022) have not explored a broader perspective of the SW basic

[5] Cycle time depends on the production capacity and corresponds to the time elapsed between the beginning and end of a cycle to complete all operations (Alvarez & Antunes Jr., 2005).

elements (e.g., sequence of steps, location flows, slack), and neither explored its integration with production status control with the support of digital technologies. This integration can potentially increase the degree of standardization of production cycles, increase the efficiency of operations, and contribute to the synchronization of processes. So, this research aims to propose a model that integrates SW and production status control by using digital technologies to support LBPC.

RESEARCH METHOD

Design Science Research (DSR) is the methodological approach adopted in this investigation. DSR seeks to produce scientific knowledge (Holmström et al., 2009) while solving problems faced in the real world (March & Smith, 1995) and contributing to theoretical developments (Kasanen et al., 1993). The artifact proposed in this investigation is the production management model, which results from the combination of LBPC, SW and production status control with the support of digital technologies. This research work was based on an empirical study carried out in a Brazilian company involved in the development and construction of residential and commercial building projects, named Company A. This company is well-known in the market for the successful implementation of Lean Production practices and had implemented the Last Planner System for more than 15 years. The main company's motivation to take part in this study was to increase the degree of standardization of critical processes. This study occurred between January and September 2022.

The empirical study was divided into four phases: (1) assessment of the existing planning and control system; (2) analysis of data and proposition of the model; (3) implementation and refinement of the model; (4) evaluation and final discussion. The first phase consisted of understanding the existing situation in one of the company's construction sites. The planning and control system was assessed, and several Quality Management System (QMS) documents were analyzed. Moreover, some workers and site logistics operations were monitored, and critical processes and improvement opportunities were identified. The research team proposed the model in close collaboration with the company's managers. The development and test phase occurred through iterative learning cycles of data collection, analysis and reflection, in which the solution was implemented and collaboratively improved. During the implementation phase, the artifact was evaluated, and at the end of the study, the proposed model's practical and theoretical contributions were identified.

PROJECT DESCRIPTION

The project comprised a residential tower and a commercial area of 15.341,13m², which started in September 2020 and was expected to finish by March 2023. This study focused on the 15-floor residential tower built on structural masonry and internal drywall partitions. Thirteen floors had the same layout, containing 12 apartments. The apartments had between 56m² and 67m² of private area and were divided into three typologies. The apartments had similar work densities, which provided an ideal base to devise and implement the planning and control model proposed in this investigation. The study was performed during the finishing phase when the interior drywall partitions were almost finished.

EMPIRICAL STUDY STEPS AND SOURCES OF EVIDENCE

The assessment of the existing planning and control system included site visits, participation in planning meetings and interviews. Consequently, important aspects were analyzed: building systems adopted, the Location Breakdown Structure (LBS), production batch sizes, the volume of WIP, visual devices to support planning and control, direct observation of vertical and horizontal material transportation operations, layout and stocks. Moreover, the master plan was translated from a Gantt Chart into a LOB using a LBPC software. As an outcome of this stage, some improvement opportunities were identified: the need to plan, standardize and synchronize critical activities based on the SW concept, and introduce the production status control with the support of digital technologies. The **analysis of data and proposition of the model** were focused on a set of critical processes, which were selected according to the following criteria: (a) a high degree of variability; (b) a large number of interdependent activities; (c) about to start activities. A protocol for direct observation of the 3rd, 4th and 5th floors' ongoing activities was applied, and semi-structured interviews with workers were carried out to map the work content of those critical activities (cycle time, sequence of operations and requirements to perform an operations cycle). Data collected included the floor location flow followed by workers, the number of workers and their distribution within the floor, the actual cycle time for each worker to execute each apartment, the trade's floor cycle time and existing procedures. Based on that data, a qualitative and quantitative analysis was conducted to compare work-as-imagined and work-as-done. The improvement propositions included a standard sequence of operations, a detailed division of work zones, a new cycle time for operations, and a production pace for the processes. The digital solutions adopted were: (a) 360° camera mounted on a hardhat and connected to a mobile app to perform offline captures and upload to a cloud-based platform to monitor actual construction progress on the web browser or app; (b) tablets to update production status, collect activity progress data, which trigger quality inspections; and (c) andons to monitor workers' check-in and check-out at different locations and to control the amount of WIP. The andon device was not used as a tool to stop the line when problems occurred and manage production alerts.

The **implementation and refinement** stage started by training managerial and production teams on key lean topics (e.g., LBPC, takt time, batch size, SW and production status control). This training also enabled managers and workers to operate digital technologies and visual devices. The implementation process focused on committing the workers to standard production cycles. Managers, researchers, and team members involved in the critical activities discussed the SW proposal in a collaborative meeting. The conversation focused on discussing the proposed standard production cycles and showing possible earnings they would have if they committed to the plan. Site visits were then made to observe the work performed, monitor production status, and discuss and refine the proposed standard. Finally, in the **evaluation and final discussion** phase, performance metrics were analyzed: the amount of WIP, apartment and floor cycle time variation, production pace deviation and batch adherence. Workers' and management team feedback was collected, and the artifact was then evaluated based on utility and easiness of use criteria, as suggested by March & Smith (1995).

Table 1: Summary of sources of evidence

Phases	Time Spent	Sources of Evidence
1- Planning System assessment 2- Improvement propositions	17 hours 30 min	Direct and participant observations; Semi-structured and open interviews; Document analysis; Photos.
3- Implementation and refinement	46 hours	
4- Evaluation and final discussion	6 hours	Participant observations; Semi-structured interviews

RESULTS

ASSESSMENT OF THE EXISTING SITUATION

The transcription of the existing master plan into a LOB (Figure 1) pointed out some problems: (i) not enough time gaps (buffers) between processes; (ii) limited process synchronization as cycle times varied from three to ten days; (iii) the continuous product flow was emphasized, focusing on executing tasks as soon as possible, and causing workflow interruptions.

A set of five critical interrelated activities was chosen for the implementation of SW: ceiling plaster lining, waterproofing, mechanical protection, and wall and floor ceramic tile (Figure 1). The site manager pointed out that keeping this set of activities on time was challenging. A major cause of this problem was the high amount of WIP: work was spread over several floors, and there were site congestions of different teams working in the same location.

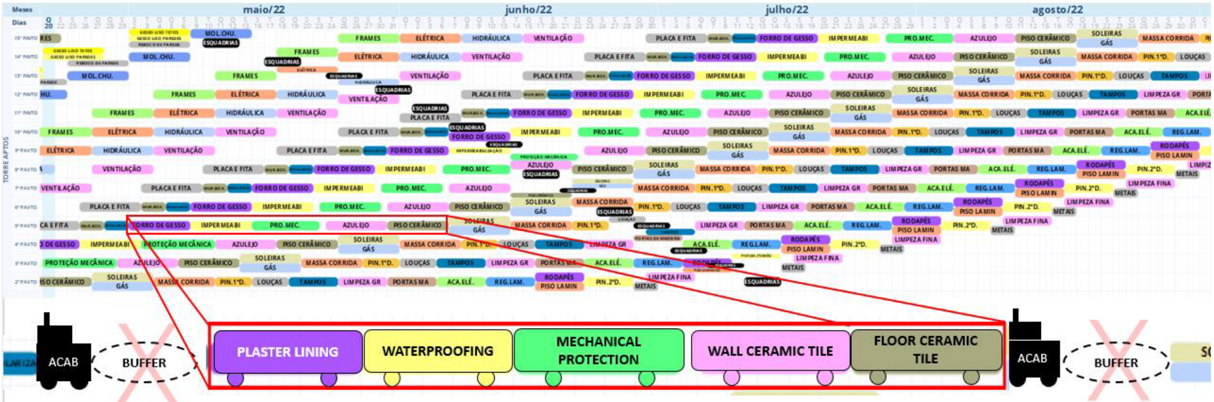

Figure 1: Master Plan and the set of critical interrelated activities selected

Figure 2a and 2b compare the initial plan and the projection of the production pace, based on existing performance, for the set of critical activities. The following problems were detected: (a) the actual production paces were different from the master plan; (b) there was a 24-day delay in the starting day of the set of critical activities; (c) waterproofing and plaster lining were being executed in parallel which caused some interferences between crews; (d) wall and floor ceramic tile actual cycle time was 16 days, i.e., longer than the 10-day planned duration; (e) wall and floor ceramic tile were planned to be executed in sequence while executed in parallel, and based on the projected production pace tendency it was not going to finish within the established deadline (September 1st 2022).

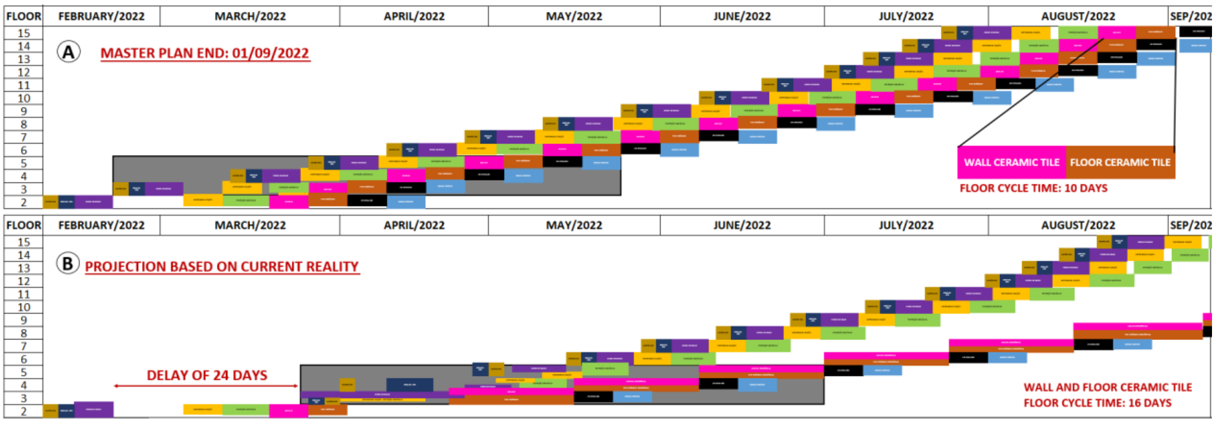

Figure 2: (A) Master plan and (B) Projection based on current reality

STANDARDIZED WORK PROPOSAL

Based on the identified delay trend, mostly related to the execution of the wall and floor ceramic tile, a future state plan was proposed considering ideal cycle times (Figure 3). The five critical interrelated activities were merged into three activities: (1) ceiling plaster lining; (2) waterproofing and mechanical protection (3) wall and floor ceramic tile. For these three critical interrelated activities, a 5-day floor cycle time was considered as well as a new crew size definition. This research paper focused on the wall and floor ceramic tile activity, as this was the one that had the highest impact on the existing delay. By implementing these improvements the new projected conclusion of the set of activities was August 19th 2022, which represented a reduction of two weeks' duration compared to the master plan.

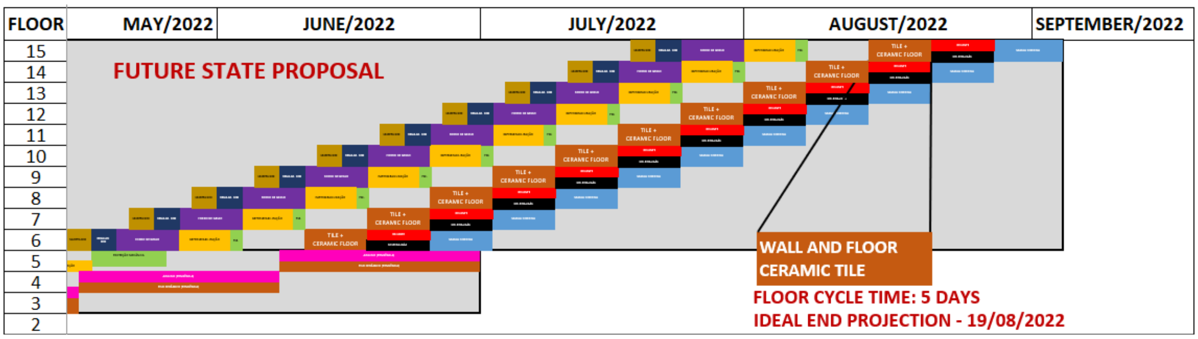

Figure 3: Future State Proposal

In order to implement SW, the future state proposal needed to be detailed, observing actual cycle times, necessary production and setup times, execution alternatives and good practices informed by workers. The aim of this stage was to balance the amount of work among crews to reach the takt time of five days per floor and synchronize the processes. Figure 4 shows the current state of the wall and floor ceramic tile, which makes the number and distribution of workers into work zones (Y-axis), durations (X-axis) and location flows explicit. It highlights that the actual floor cycle time is sixteen days, while it was planned for ten days.

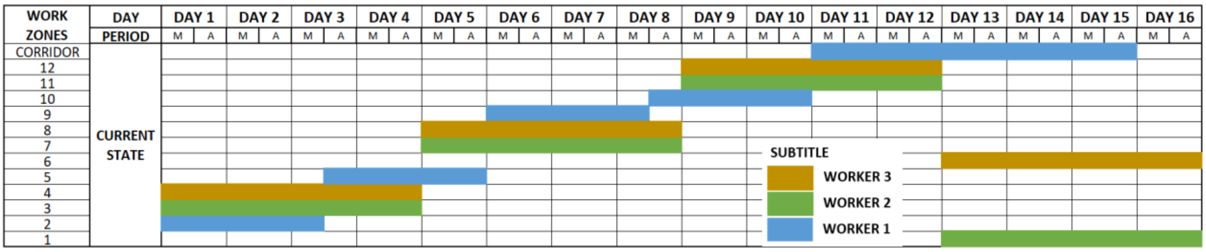

Figure 4: Current State – Wall and floor ceramic tile

The current state of each critical activity was initially discussed with the site manager and the subcontractor. Based on that, a new crew size was established. After that, the distribution of work was discussed with the workers involved in the task, resulting in the proposal of the first version of the SW. This proposal comprised the elements: takt time, worker cycle time, standard floor location flow, followed by workers and standard sequence of operations in each apartment. In the second version of the SW proposal, some types of slack were included. Figure 5 presents the SW sheet for wall and floor ceramic tile.

In order to commit workers to the implementation of SW, managers and researchers promoted a meeting with all of them to discuss the plan and explain the benefits to all parts. It was emphasized to workers that they would benefit from better working conditions, increase in the learning effect and production predictability, and consequently, raise their earnings.

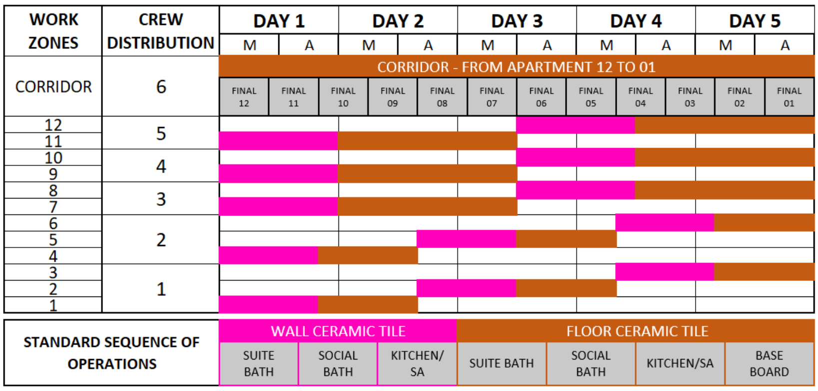

Figure 5: First Standardized Work Proposal – Wall and floor ceramic tile

INTEGRATION OF STANDARDIZED WORK AND PRODUCTION STATUS CONTROL

After defining the SW, control routines were proposed to achieve takt time and synchronize interrelated activities. The LBS played an important role in defining production control cycles. The company was used to allocate crews to floors. However, it was decided to reduce the production batch size to one apartment to make it easy to control each operation flow of each apartment (12 apartments per floor) and perform quality inspections. Nonetheless, the production pace control was still being controlled per floor (13 floors total) so that it could be compared to floor takt time. Reducing the batch size was important to improve the commitment of crews to the location flow and to encourage them to take proactive measures to achieve the proposed apartment cycle time. This was named hierarchical work zone control, as different work zone levels enabled different location-based controls.

The inclusion of different types of slack was due to the need to cope with the variability in workers' productivity, as teams used to work in a fragmented way. The main types of slack adopted were: multifunctionality of some subcontracted crews, time buffers, and space buffers, e.g., apartment and corridor areas to be produced which had no worker assigned by the one that finished their assigned apartments before the floor takt time.

With all these decisions, visual devices, digital technologies and control routines were implemented to promote transparency and increase understanding and commitment to plans and standard working routines. Figure 6 shows a visual device used on each floor to make production goals explicit for each worker of ongoing activity (apartment takt time, time and buffer, location flow and standard sequence of operations). Other visual solutions were also adopted: workers' names were written close to the entrance door of the assigned apartment, and spray was used to mark the best sequencing of ceramic installation to encourage repetition in operations.

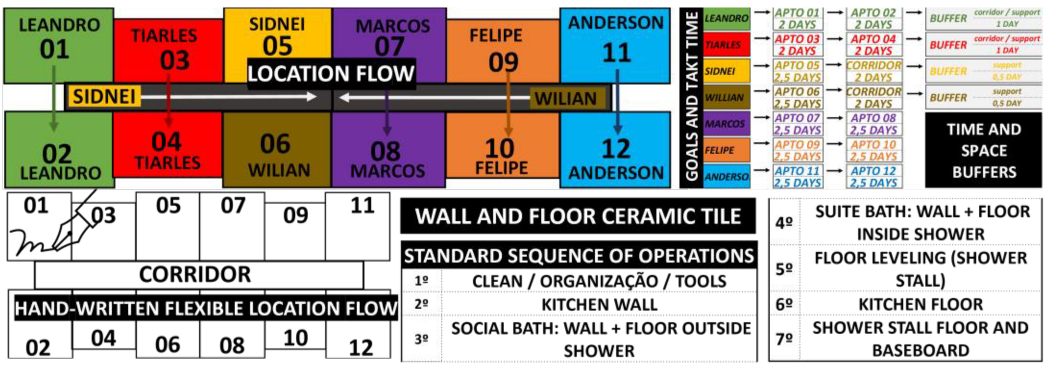

Figure 6: (1) Visual device that displays batch sizes, workers allocation and location flow, apartment takt time, time and space buffers and standard activity sequence; (2) Example of flexible allocation visual device.

An LBPC software was used to produce the plan, support control routines and allocate workers. A key step in allocating workers to work packages was following the planned floor location flow and prioritizing the execution of the same apartment typology to promote the learning effect in order to increase productivity. After some production cycles, the need for flexibility in assigning workers to their activities in work zones was observed due to workforce turnover, variation in production pace and work absence. This was done by using a visual device that allowed some degree of flexibility in the allocation of labour, as shown in Figure 6.

SUPPORT OF DIGITAL TECHNOLOGIES TO CONTROL THE PRODUCTION STATUS

The production status control matrix was devised to control the amount of WIP while assigning activities and work zones to workers. It can be considered as an application of the pull production concept proposed by Hopp & Spearman (1996): activities are triggered by the status of the system. The aim of this visual device was to improve communication between trades, and enhance data accuracy and traceability of process status. The source of data was the check-in and check-out control process, which allowed the start and finish times of different operations to be obtained. Three different mechanisms were used (Figure 7). Initially, paper tables were already adopted by the company, producing a daily manual report on activities status – besides the lack of automation, that solution resulted in inaccuracy for start and finish times, as data collection was performed generally once a day and sometimes not in all work zones. Then, two other mechanisms replaced it: a cloud-based electronic spreadsheet with mobile data collection, which produced a reduction of data collection and processing times, increased data accuracy and provided an overview of the production status in each work zone (Figure 7a); and a semi-automated status registration using an andon system (Figure 7b).

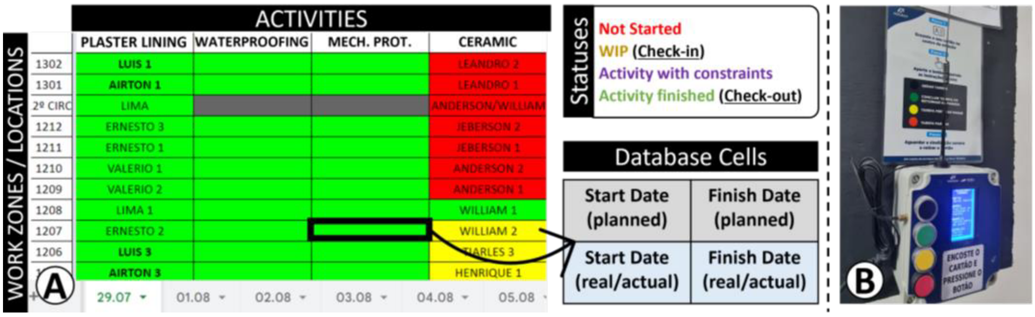

Figure 7: (a) Production Status Control Matrix and database that originates the statuses, and (b) electronic device to self-register actual start and finish (e.g., Andon).

Workers allocation was done in a mobile app which automatically updated the LBPC software, and workers received a message about the updated assigned activity and work zone. This information was also updated to the andon system, enabling workers to use their tags to obtain their assigned activity and update its status. This app was used to improve WIP control, as workers should follow the assigned location flow. The managerial team started anticipating allocations 1-2 weeks before activity should start accordingly to the production status. To some extent, this system lacked the flexibility to allocate workers and change locations flow. But the check-in and check-out mechanism automatically updated a database that stored planned and actual start and finish dates. This information allowed the production status matrix to be updated in real-time and provided an overview of the status of each location, represented by different colours (Figure 7a). Also, this database was the source of information for all production performance graphs (see the following topic). The 360-photo database, located on a cloud-based platform, was useful to support tracing WIP, work completeness and production cycles by location. It was also used to assess start conditions, site organization and stocks. Some constraints and the need for additional logistics work were identified, resulting in the assignment of new tasks for managers and crews. All the analyses made through this platform were triggered by the production status control.

DISCUSSION

Several different production metrics resulting from LBPC were used in this project: cycle time (per apartment and floor), batch adherence (per floor) and production pace deviation (per process). Figure 8 presents graphs generated for wall and floor ceramic tile. Figure 8a shows that, even though this process had not started at the initially planned start date, it finished on time. In fact, balancing the amount of work among employees allowed the floor delivery pace to be lower than it was initially planned. Figure 8b indicates that this was achieved, i.e., actual cycle times ranged from six to seven days per floor. On the 12th and 13th floors, there was an increase in cycle time due to sharing the resources with the 2nd floor. Hierarchical work-zone control was fundamental to this process, as it enabled different location-based controls: even though apartment cycle times (a lower control level) varied inside the floor production cycle, floor takt time could be accomplished (a higher level of control).

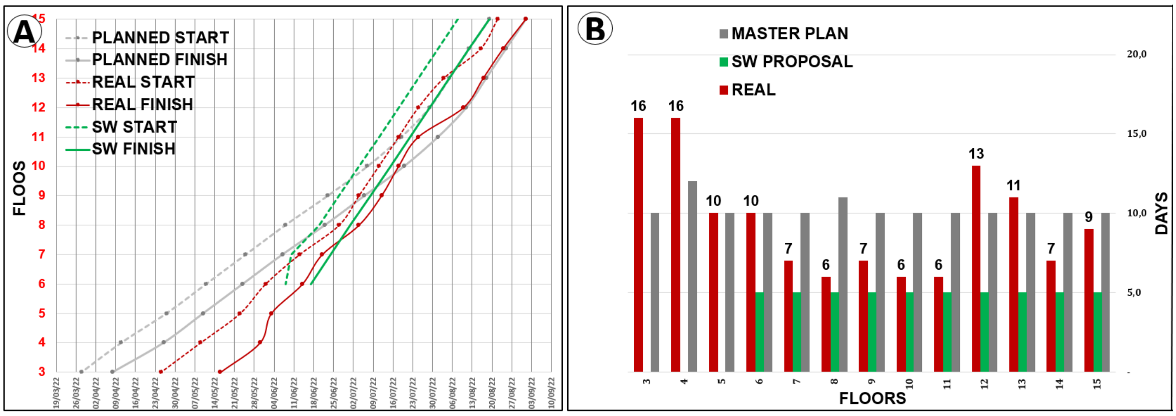

Figure 8: (A) Batch Adherence and (B) Cycle Time – Wall and floor ceramic tile

Two graphs were created to analyze the impact of SW on the set of interrelated activities (Figure 9). Figure 9a plots the production pace deviation by process, showing a trend of process synchronization. Figure 9b shows the evolution of cycle time, indicating a trend of reducing both duration and variation. This confirmed that the combination of SW and production status control was successful in terms of implementing production improvements towards process synchronization.

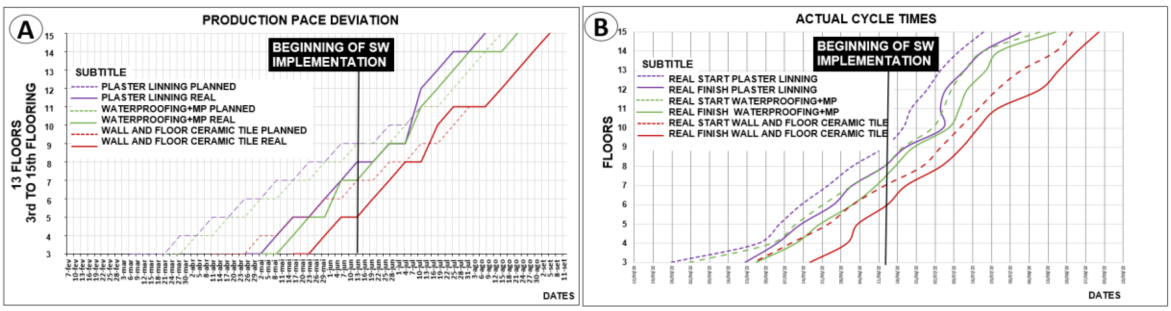

Figure 9: (A) Production Pace Deviation and (B) Actual Cycle Times-Interrelated Processes

Implementing SW enabled stabilizing processes' cycle time, reducing work zones congestion and displacements. The focus on the execution of the same apartment typology generated learning and increased the crew's productivity. The effects of the SW and production status control combination enhanced subcontractor trust and the prediction of the amount of work ahead and monthly incomes. These reduced workforce turnover, a problem identified during the first production cycles. Monitoring production status successfully supported work allocation, based on the pull production principle, which increased WIP control and helped crews to anticipate initial conditions and problems and report them to managers, so they could solve them before starting their activity in that location. Digital technologies also provided a key support in quickly obtaining accurate, traceable and transparent construction progress data, which was used to make production adjustments when needed. Visual devices, such as the production status matrix and metrics report, supported weekly meetings with subcontractors to have a production overview, detect rhythm deviations, align goals to follow the proposed plan and make the necessary adjustments. The need to adopt slack was endorsed during production cycles to cope with productivity variability. However, this mechanism was not enough. Anticipating the requirements to perform an activity beforehand was also important to eliminate constraints, but this was not fully explored in this investigation. This was made evident by some problems identified, such as the unavailability of crews to execute the 2nd floor, which increased the cycle time of the wall and floor ceramic tile on the 12th and 13th floors, as the same crews had to execute these in parallel. Also, problems with pipe leveling on the slab surface were not identified in advance and did not allow the installation of the kitchen floor on time and generated additional activities. Therefore, using digital technologies to analyse ideal conditions to perform activities and controlling task completeness while considering quality standards play a key role in the successful implementation of SW and process synchronization.

INTEGRATED CONTROL MODEL AND EVALUATION

The proposed model for integrating SW and Production Status Control is presented in Figure 10, being divided into five main steps. The model was evaluated accordingly to its utility and easiness of use. Regarding the utility construct, the model contributed to the implementation of collaborative processes in LBPC and the level of standardization, promoting team engagement and increasing the reliability of the production system. By encouraging participation and work autonomy, SW provides a suitable balance of standardization, flexibility and continuous improvement. In fact, workers provided feedback on their learning, and productivity increased along standard production cycles. The model also increased workers' autonomy by providing a clear scope of flexibility bounded by the standardization of operations: location flows and apartment cycle time were part of the standards, while workers could change operation sequencing during execution. Consequently, the model provided mechanisms to increase the stability of processes' synchronization and production cycles. Regarding the ease of use construct, it was observed that the model enabled the understanding of LBPC practices and concepts, as well as made information available to support decision-making effectively and transparently.

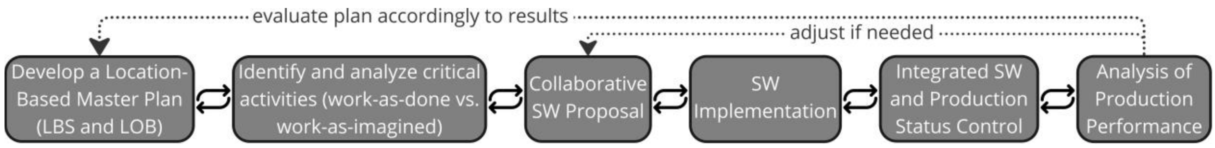

Figure 10: Integrated Control Model of SW and Production Status to support LBPC

CONCLUSIONS

The main contribution of this investigation is extending the use of LBPC to the very operational level, by adapting the SW approach, developed in manufacturing, into the construction industry. This study has also explored the use of production status control by using digital technologies. This model is based on the assumption that the implementation of the Lean Production Philosophy in construction must emphasize the management of variability, rather than simply trying to eliminate it. Collaborative processes involving the workforce, and the use of visual management supported by digital technologies play a key role in the model. This results in a set of lean metrics and concepts that are effectively used in production management: takt time, cycle time, slack, standard floor location flow, standard sequence of operations, production status, and work-in-progress control. Therefore, the model can be understood as a mechanism to systematically manage variability and uncertainty in LBPC (workforce and processes) and increase the degree of standardization of processes while having short feedback cycles to promote adjustments while monitoring the construction progress. The control model must seek an equilibrium between standardization, flexibility and autonomy in production processes. The proposed model still needs to be refined to provide a robust decentralized management system. Further studies should consider: (a) implementing the model in projects with lower levels of repetitiveness; (b) investigating other digital technologies for monitoring production; and (c) further investigating requirements (standard kits) and slack to avoid the negative impact of variability.

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A LOGISTIC FRAMEWORK TO ENABLE TAKT TIME PLANNING

Raquel H. Reck[1] and Marcus C. T. Fireman[2]

ABSTRACT

Takt Time Planning (TTP) methodology has gained growing popularity in lean construction, with the aim of improving workflow and increasing production stability. Despite the numerous research efforts surrounding TTP, there is a gap in understanding how logistics planning should support TTP in a construction project. This study presents a framework for developing logistics in a construction project that uses TTP as its planning method. The framework consists of four drivers: (a) equipment sizing, (b) layout risk study and analysis, (c) material management, and (d) structuring of daily routes and routines. The results show that the integration of TTP into the logistics framework allowed for the design of the production system to ensure Takt, and to structure a rapid response to the variations found during the LPS control cycles. Hence, the project deadline was reduce by 16.4%, or 4 months.

KEYWORDS

Takt Planning, WorkFlow, Last Planner System, Logistic

INTRODUCTION

In the last decade, it is possible to observe a growing application of the Takt planning method in the lean construction. Among the main benefits achieved with the methodology, we have better team organization, better transparency, reduction of handoffs between sequential teams, reduction of cycle time, increased productivity, reduction of project duration in construction, among others (Yaw et al., 2020; Dlouhy et al., 2019; Binninger et al., 2018; Frandson et al., 2014).

Takt Planning is a structured planning method that brings a perspective of workflow and rhythm to civil construction, since it organizes the sequence of locations that should receive tasks in a construction site and, at the same time, synchronizes the execution of these tasks around a Takt time (Frandson, 2019). Takt time is a unit of time that represents the rate at which a product must be completed to meet customer demand in a specific period of time (Hopp; Spearman, 2004). According to Binninger et al (2018), one of the differentials of Takt Planning, when compared to traditional methods of construction planning, is the fact that services are produced at a constant rate, allowing a reliable pre-planning of activities. Gardarson et al (2019) points out that Takt Planning can be represented as a train with several wagons that move through the areas of a project. In this format, the wagons are different groups of workers who complete a set of tasks before moving to the next area, being followed by another wagon of workers who will complete their respective tasks (Gardarson et al, 2019).

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Vatne and Drevland (2016) signal the important role of logistics for the successful application of Takt. According to Lehtovaara et al. (2019), one of the main barriers to Takt Planning is precisely logistics planning and material control. Tommelein and Emdanat (2022) corroborate this thinking, and suggest a correlation between Takt and logistics planning. If, on the one hand, Takt analysis is an input to logistics planning, on the other hand, logistics can become a bottleneck for the application of Takt, since the dimensioning of transport equipment, the space for storage and movement interference of equipment can make a Takt unfeasible to be applied in a project (Tommelein; Emdanat, 2022).

Recently, Al Barazi et al (2021) demonstrated the potential of simulation methods, such as Agent Based Modeling, for logistics simulation in vertical construction sites, with the goal of fulfilling a hypothetical Takt planning. In this study, it was possible to identify the best number of equipment according to variables such as elevator capacity and speed, storage capacity on site, lunch and snack time, etc. Tetik et al. (2019) set out to analyze the benefits of using appropriate logistics solutions for Takt application in construction. The research focused on the logistics solution of material picking and kitting in Assembly and Logistics Unit (ALU), identifying that the main benefits were related to the reduction of material waste, ability to follow the predetermined Takt sequence, and a better quality of acquisition (Tetik et al., 2019).

While recognizing the significance of logistics in realizing the expected advantages of Takt planning, there is a lack of practical research that illustrates how to establish logistics in a project to fulfil predetermined Takt time. Hence, it is crucial to devise a Takt planning while simultaneously designing and executing logistics strategies for the construction site. The purpose of this article, therefore, is to demonstrate the utilization of a logistics framework to fulfil Takt planning through a case study.

METHOD

The research is positioned as Design Science Research, in which innovative constructions (or artifacts) are developed, designed to solve classes of problems encountered in the real world and, at the same time, make theoretical contributions (Lukka, 2003). The artifact proposed in the present study is a logistics framework motivated by the systematics of Takt time planning. In this type of study, the starting point for conducting the research is the knowledge of a set of practical problems (Van Aken, 2004), in this case, the design and execution of logistics strategies that guarantee the transformation of the construction site to comply with the Takt time requirements.

The framework was developed during a case study about a housing project with 23 residential towers in 5-storey structural bricklaying, totaling 1180 apartments, divided into 3 distinct contracts (Figure 1).

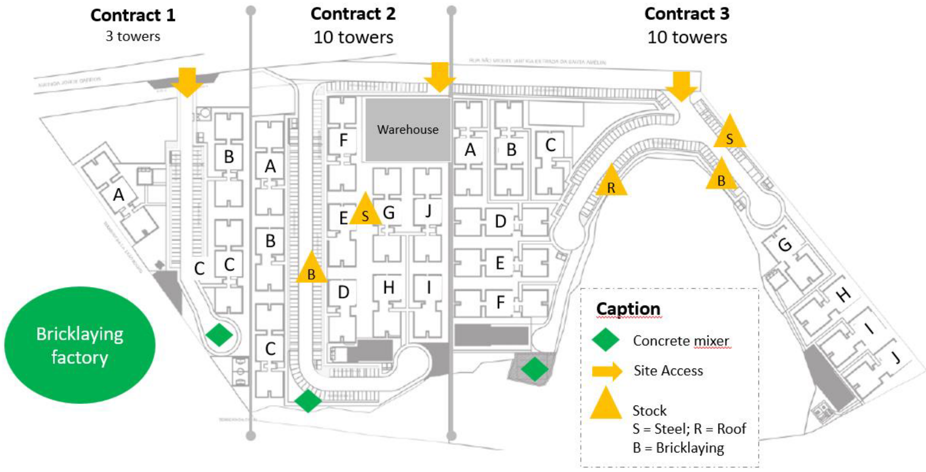


Figure 1: Location of the towers and construction site facilities

The contractor of this project was interested in implementing Lean practices, hiring a consulting company for this purpose (implementation period from September 2021 to February 2022, total of 6 months). At the time of the diagnosis carried out by the consulting company in September 2021, only masonry structural walls and structured concrete slab activities had started, and the project still had 15 months left until its completion (September 2021 to October 2022). Due to the project being divided into 3 contracts with the same due date, during the diagnosis phase there was a scenario of a large amount of work in progress, since all 23 towers had initiated structural activities, but none of them had advanced to the 5th floor. In this regard, the deadline, inicially October 2022, pointed to a 5-month delay trend, going until March 2023.

Thus, in addition to Last Planner System routines, we proposed the deployment of a TTP and a logistics system that would allow the project to be delivered on time. The biggest challenge in this project was to scale the logistics system, as well as to be able to maintain the Takt of the productive activities, since the construction site had approximately 75,000 m², 800 employees during its peak of execution and a complex system of material and transport centers, as shown in Figure .

This research presents three distinct steps: (a) definition of Takt and structuring of the logistics system; (b) development of logistics strategies; and (c) evaluation of the logistic system implemented. The development of these steps is described in detail below. As sources of evidence it is possible to highlight: (i) participant observation of the authors of this paper at the construction site and at LPS meetings, acting as project consultants; (ii) reports on the status of the consulting project, periodically developed during the consulting; (iii) result and process indicators applied during the consulting period until the end of the construction project; and (iv) logistics checklist (Fireman et al, 2023).

DEFINITION OF TAKT AND LOGISTICS FRAMEWORK

Takt definition was carried out according to Equation 1 , in which we used 80% of practicability, because the construction site presents horizontal characteristics and external activities, which were very affected by climatic conditions. The available time, number of repetitions and number of activities vary according to activity groups, called "trains" in the case study, and assumptions of initial projects. It is important to point out that although the practicability factor is sometimes implicit in the calculation of available time in the literature, here we prefer to use it explicitly.

$$Takt = \frac{available\ time\ *\ 80\%\ practicability}{(repetitions + number\ of\ activities - 1)}$$ Equation 1

To define the Takt, a mapping of the construction sequence was designed, and we identified the existence of 17 internal and 9 external activities for each Takt area. However, at that time, there were still restrictions with long lead time that had not been hired, for example the ceramics tiles, which would take 180 days, and the materials for gas system installation that had a lead time of 90 days. Due to these factors and prerequisites, such as safety buffer and executive sequence restrictions between internal and external activities, the Takt application strategy for the entire construction site was divided into groups of activities, creating 5 trains, as described below and outlined in Figure 3:

a) masonry structural walls and structured concrete slab activities had already started and had no initial prerequisite, thus, their Takt was calculated separately;
b) train 1 corresponds to electrical and plumbing installation activities, waterproofing and cementitious floor underlayment, without time restrictions, but not yet started;
c) train 2 corresponds to gas system installation and gypsum coating activities (due to gas lead time this activity train would have less time available than train 1);
d) train 3 corresponds from ceramic tiles activities until the end of internal activities (it would also have less available time than train 2 due to ceramic tiles lead time);
e) train 4 corresponds to façade activities, which can only start when the first roof top structure of the towers is completed;
f) train 5 corresponds to façade activities after the first window installation (internal activity), and must be completed one month before the end of the work.

<table>
<tr><th></th><th>Takt Area</th><th>Repetitions</th><th>Number of Activities</th><th>Lead time (days)</th><th>Available time (days)</th><th>Takt (days)</th></tr>
<tr><td>masonry structural walls</td><td>Apartments</td><td>69</td><td>1</td><td></td><td>204</td><td>2,37</td></tr>
<tr><td>structured concrete slab</td><td>Apartments</td><td>82</td><td>1</td><td></td><td>210</td><td>2,05</td></tr>
<tr><td>Train 1</td><td>Flooring</td><td rowspan="3">115</td><td>3</td><td></td><td>283</td><td>1,94</td></tr>
<tr><td>Train 2</td><td>Flooring</td><td>2</td><td>90</td><td>224</td><td>1,54</td></tr>
<tr><td>Train 3</td><td>Flooring</td><td>10</td><td>180</td><td>220</td><td>1,42</td></tr>
<tr><td>Train 4</td><td>façade modules</td><td rowspan="2">59</td><td>5</td><td></td><td>219</td><td>2,78</td></tr>
<tr><td>Train 5</td><td>façade modules</td><td>4</td><td></td><td>170</td><td>2,19</td></tr>
</table>

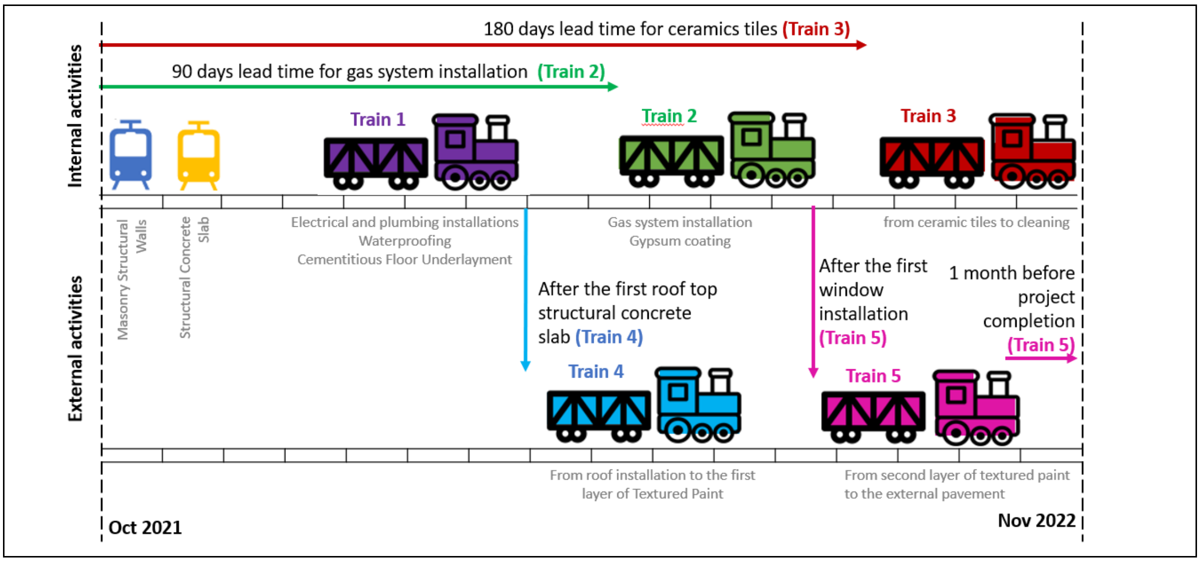


Figure 2: Takt Calculation table

Soon after the definition of the planned Takt, it was necessary to establish logistical planning and control that would allow to meet the TTP. Thus, the framework presented in Figure 3 was proposed, containing four drivers: (a) equipment sizing; (b) layout potential risk study and analysis; (c) material management; and (d) structuring of daily routes and routines. Evaluation of these drives is presented in Fireman et al (2023). In this article, we will present the use of this framework as a logistic strategies structurer carried out in the analyzed case.

Figure 3: Logistic Framework

EQUIPMENT DRIVER

Since demand sizing is done by input, a total of 48 inputs were studied. This was carried out through the Takt area, considering the storage of input in batches and the number of batches that can be transported by equipment (Figure 4). Thus, as an example, for each apartment unit, 73 sqm of ceramic tiles is required. These are transported in boxes, which can store 2,12 sqm of ceramic tiles each. Each pallet can carry 32 boxes and only 5 pallets can be transported by each truck, due to volume and weight restrictions. At the end, as shown in Figure 4, 197 ceramic tiles travels are required to supply the 1,180 apartments (Takt areas).

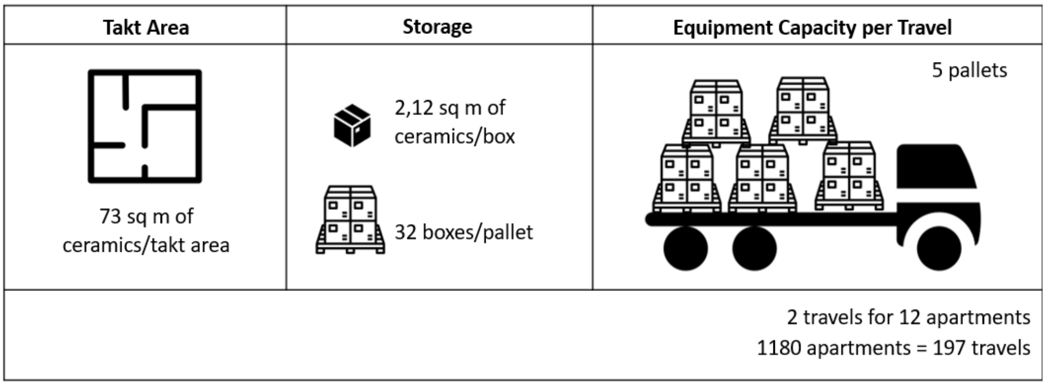


Figure 4: Example of quantification of materials by input and Takt area

For the equipment to meet the TTP, it was necessary to size the number of travels per type of equipment per input, characterizing the necessary demand. Soon after, this demand was compared with the current capacity of the equipment on site (data collected daily during the project). Table 1 presents the comparison between demand and capacity of critical equipment. Since demand is bigger than capacity, it was necessary to exchange supply equipment for input, and a fuel supply pump was allocated on site to reduce the set-up time of such equipment.

Table 1: demand versus capacity of critical equipment

Equipment	Demand (peak)	Capacity (peak)
Munk	73 trips per day	73 trips per day
Backhoe loader	62 trips per day	57 trips per day

LAYOUT DRIVER

To evaluate potential logistics risks, a layout study was carried out in an analogical manner, where in which each frame represented a period of time and a specific train. Thus, every 3 months it was highlighted in the frame where each of the 5 trains plus the masonry structural walls and structured concrete slab activities would be located. In this way, it was possible to evaluate risks of crossing different workflows, storage locations closest to the towers in construction and pre-assembly locations, such as cutting and folding steel rebars and concrete mixer. Figure 6 shows this layout analyses. Vertically, we have the different trains in different colors, and horizontally each column corresponds to 3 months of the project.

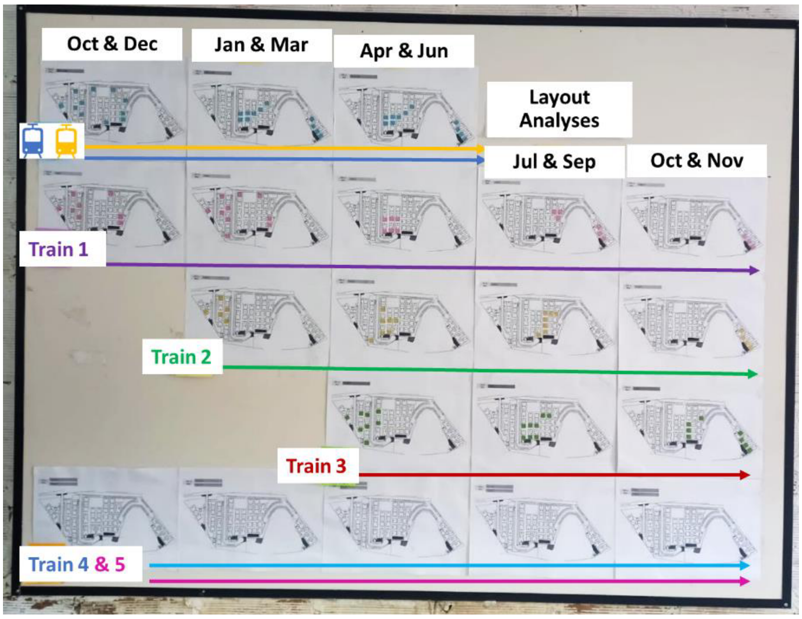


Figure 5: quarterly Layout Study

Then, Figure 6 presents a detailed study for the site's peak working week. It presents, the routes between pre-assemble location (such as cutting and folding steel rebars and concrete mixer) and storage (such as material stocks and warehouses) to workstations. Thus, it was possible to assess the density of workflow and identify the main transportation risks.

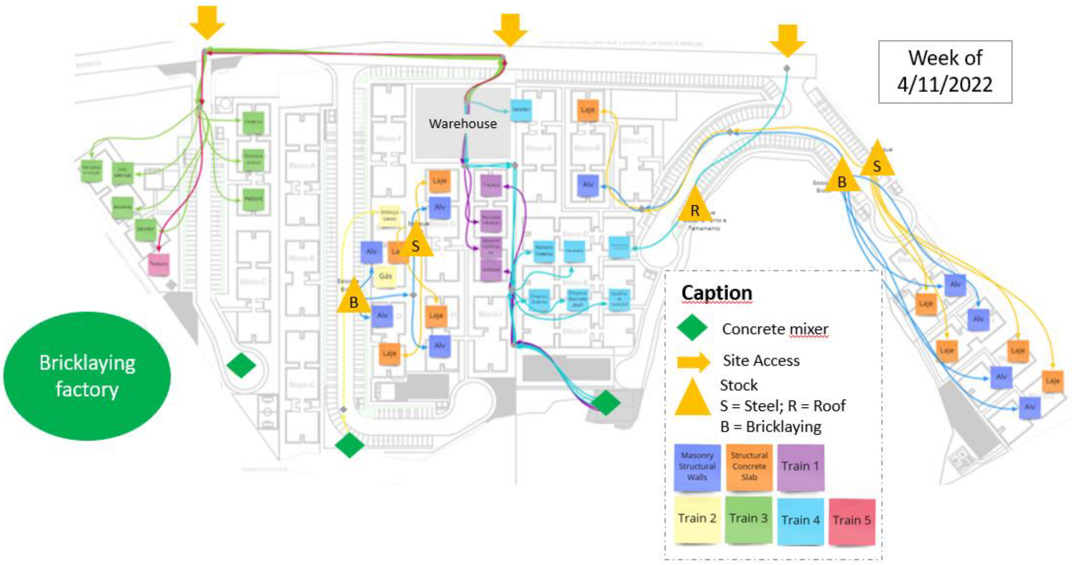


Figure 6: study of routes between production/storage locations and workstations

MATERIAL MANAGEMENT DRIVER

From the tools developed in the layout driver, it was possible to identify different potential risks for material management. The main ones were:

a) assess whether the flow of sand (number of travels per day) would impact the movement of materials at the site, since all concrete was produced at the site in only 3 concrete mixers;

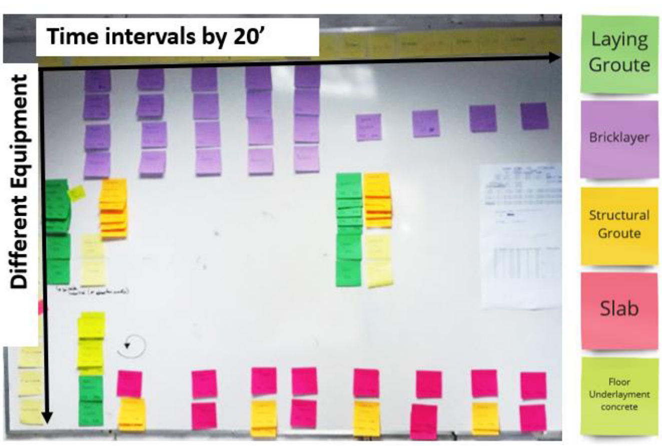
b) define the supply flow of the cementitious floor underlayment, mainly identifying the equipment to be used to avoid possible obstructions to pumps due to density and gravel incorporated into the mixture;
c) definition of evening supplies to avoid route jamming during the teams' working hours;
d) definition of ceramic tiles storage locations at the manufacturer and in front of the towers, since 983 pallets of this input would be needed to build the 1,180 apartments (as discussed in the equipment lever);
e) considering the ceramic tiles to be supply to the floors via a small crane by boxes, since each floor would need 10 pallets, or 320 boxes;
f) considering the installation of the crane in the elevator shaft of the towers in order to vertically supply the apartments;
g) definition of roof tile storage and supply, since it would be necessary to store 5,784 roof tiles for each tower module (the construction project has 59 modules, totaling 341,256 roof tiles for all towers);
h) definition of wood storage and supply for the roof structure, since it would be necessary to receive 4 trucks every 2 weeks (supplier restriction), which could supply the demand of 9 modules.

Thus, during LPS meetings, together with the warehouse manager and the logistics manager, the logistics strategies for these materials were discussed and applied on site.

ROUTE & ROUTINES DRIVER

After defining the three previous levers, it was necessary to implement the equipment Kanban and Check in/out tools for structuring of routes and routines. These tools had as input the sizing of daily goals from TTP and the demand for materials, dealt with in previous stages of the framework.

The equipment Kanban had 5 inputs: laying grout, bricklayer, structural grout, input of slab and cementitious floor underlayment. Kanban was partially implemented - it was not used for hands-off management between workstations and pre-assemble location and storages. But, according to Figure 8(a) the demand for each input was analyzed for each supply equipment (vertical) per hour (horizontal). Initially, the construction team had a certain resistance to the implementation of this tool, but eventually it was used for critical analysis of supply, involving the production engineer, the logistic manager and the foreman.

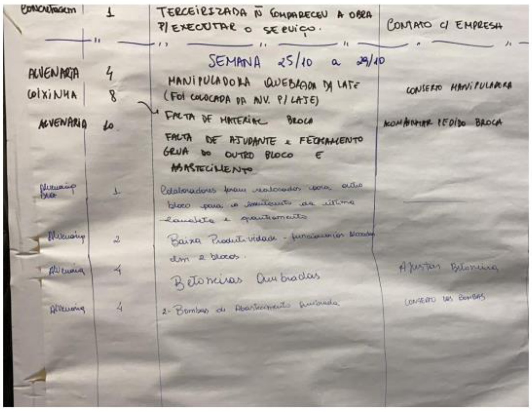


(a) Kanban by equipment (vertical) and time interval (horizontal);

(b) check in/out routine per work front

Figure 7: tools developed for leveraging routes and routine

Check in/out was defined for 13 services (see Figure 7 - b) and played an important role in solving logistical problems at the site. There were a significant number of Reasons for Non-Compliance regarding equipment breakdown and supplies delay. These were reported daily during the Check in/out routine by team leaders. These observations were acted out in daily action plans (see Figure 8a) and helped structuring a fast-problem-solving flow for equipment (see Figure 8b). Because of that, we established more frequent preventive maintenance for certain equipments, such as the external plaster projection pump, shown in Figure 8(b).



(a) notes from check in/out;

(b) evidence of breakage in the external plaster projection pump.

Figure 8: examples of equipment breakdown and help chain management

DISCUSSION

The benefits, as indicated in the literature (Yaw et al., 2020; Dlouhy et al., 2019; Binninger et al., 2018; Frandson et al., 2014), that have been observed with the implementation of the logistics framework are:

a) improved team organization, achieved through the use of layout, material, routes and routines drivers, risk analysis of layout, defining strategies for managing storage and supply of materials, as well as structuring daily production routes and routines.
b) enhanced transparency, facilitated by the visual board implemented in this case study, as in the quarterly layout study (Figure 6), route study (Figure 7), Kanban (Figure 8), and check in/out (Figure 8);
c) increased productivity through the check in/out routine, which facilitated the structuring of a fast-problem-solving action plan for any issues that arose daily.

It was also possible to make progress in sizing the equipment and material to meet the production demand defined by the Takt planning through the equipment and material drivers, which was a barrier described by Lehtovaara et al. (2019). However, logistics strategies such as material picking and kitting in the Assembly and Logistics Unit (ALU), as described by Tetik et al. (2019), could represent an even greater advancement in this driver. Tommelein and Emdanat (2022) have pointed out this synergy between Takt and logistics for the dimensioning of transport equipment, storage space, and interference of equipment movement, which are reflected in the equipment, layout, and materials drivers described in this paper. However, the proposed framework also advances the structuring of routes and routines on the construction site. Therefore, the structured use of these four drivers allowed for the design of the production system to ensure Takt, as pointed out by Tommelein and Emdanat (2022), and a rapid and structured response to the variations found during the LPS control cycles.

Figure 9 presents a comparative analysis of the projected duration. At the time of diagnosis, while there was no prospect of starting any activity other than masonry structural walls and structured concrete slab activities, and without Lean practices implemented, the project duration was 5 months after the contract, totaling 390 days. The actual duration of the project was 326 days, a 16.4% reduction in relation to the projected deadline. In Figure 9, it is possible to identify that if the proposed deadline reduction suggested by TTP was achieved in its entirety, the project end date would be October 2022, according to the contract, representing a potential time reduction of 27.9%. The main roots causes of problems that prevented from the reduction propose by the potential reduction are related to the above-average weather conditions and delays in the supply chain due to lasting COVID-19 effects.

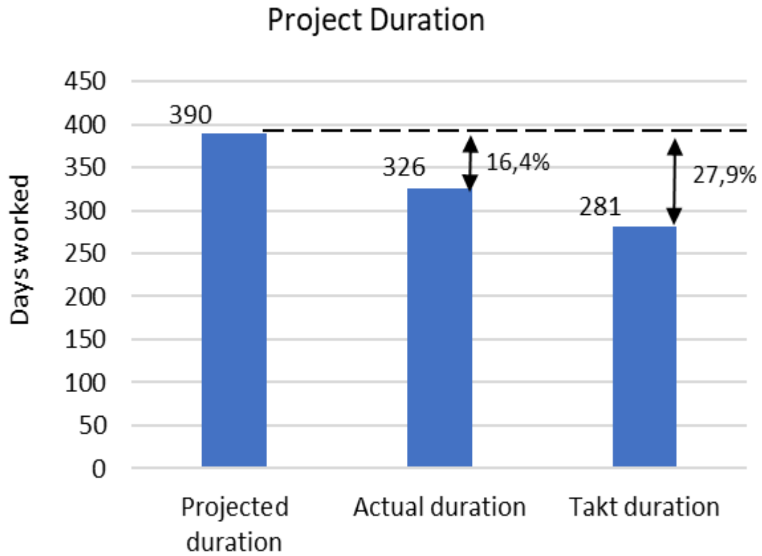


Figure 9: evaluation of the framework drivers

Even with these two roots causes, we understand that the joint application of a logistics framework and TTP contributed to achieve a good performance on the project. But, a limitation of this study is that there is no data to confirm that the 16.4% of reduction was only motivated by the joint application of them.

CONCLUSION

This article fulfills its goal, since it presents the development of logistics strategies considering the drivers of the proposed framework and the TTP. The drivers are: (a) equipment sizing, (b) layout risk study and analysis, (c) material management, and (d) structuring of daily routes and routines. These drivers allow a multivariate analysis with different sources of evidence to identify problems and logistics potential risks, allowing more efficient action plans and acting directly on the root causes. The proposal of this framework can structure both the development and the evaluation of logistics systems to support TTP. In this paper, only the development was explored, but publications focusing on evaluation, such as Fireman et al (2023), can assess the logistics strategies in different contexts, fostering good practices that guarantee Takt enforcement.

Another important paper output was to bring light to some difficulties faced when applying Takt planning. For example, the artifice of creating 5 trains was applied to circumvent some obstacles identified during method application, such as the long lead time restrictions of ceramics tiles and gas system installation or the interference between some internal and external activities, differently from Gardarson et al (2019) approach which these problems did not exist. These obstacles demonstrate that the best time for applying TTP with a focus on the project's macro strategy is before the project begins. If the method it is applied during the project, some services may not act synchronized to a single Takt, and it would be necessary to use more than one train, as present in this paper.

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DO FAILURES IN A TAKT PLAN FIT THE FMEA FRAMEWORK?

Becca Apgar[1] and James P. Smith[2]

ABSTRACT

Few studies have explored takt planning failures and how they might be better prevented. Recently Failure Modes and Effects Analysis (FMEA) has been proposed as a framework for actively preventing failure in takt planning projects. This project tests case study failures against the proposed FMEA framework as a first step to determine whether a FMEA-takt plan framework can help identify and respond to takt plan failures. In this case study, takt planning was implemented halfway through the construction of five large data centers in Utah, USA. The project was repetitive, enabling a takt of one day despite the large size of the project. Any variance from the schedule (a takt plan failure) was associated with a specific task and marked in their weekly work plans (WWPs). A reason for the variance was identified. These variances were compiled for all available WWPs and are compared to the failure categories proposed in the FMEA-takt plan framework. This study shows that the FMEA-takt plan framework is feasible with minor adjustments to account for failures in takt plans that are due to variables that are beyond the scope of a takt plan, such as unforeseen conditions or extreme weather.

KEYWORDS

FMEA, process, takt planning (TP), variability, work flow.

INTRODUCTION

Over the last ten years, takt planning has been developed and applied in the construction community. Starting with Frandson et al. (2013) detailing takt planning, research has been conducted with the goal of understanding its impact and value in reducing variability and improving efficiency.

As research continues to explore takt planning, the question becomes why does it continue to be an area of focus for academia, and why does it work well? Takt planning is especially effective because it emphasizes eliminating bottlenecks, resulting in a decrease of compounding delays (Tommelein et al., 2022). Takt gives immediate feedback which allows for early recognition of whether the project is running according to schedule or behind schedule. Takt increases transparency but it also structures work which allows for an easy understanding of next steps (Frandson & Tommelein, 2014; Kujansuu et al., 2020). Takt time reduces throughput time and enables projects to finish in shorter amounts of time (Binninger et al., 2017). Takt has great benefits, however it requires significant effort at the start of the project and dedication to maintain it throughout the project (Frandson et al., 2013). Due to this effort, when takt plan

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failures occur it can be harder to keep the takt plan through to the end of the project (Alhava et al., 2019).

Takt plans have been compared with other scheduling methods, and recently combined with a Failure Modes Effects and Analysis (FMEA) framework to better combat failures that occur within a takt plan. FMEA is a method for identifying possible errors in a system or process with the goal of better avoiding the errors in the future (Carbone & Tippett, 2004). FMEA has been used in other industries, such as medicine and manufacturing to improve complex processes and has the potential to greatly benefit production control methods in construction. Lehtovaara et al. (2022) outlined how to apply FMEA to takt plans.

This paper specifically focuses on testing the categorization of takt plan failures within the FMEA framework outlined by Lehtovaara et al. (2022). In their paper, they defined three failure categories for a FMEA-takt plan framework: wagon content failures, wagon handoff failures, and takt train failures. Wagon content failures occur within a wagon or one trade. Wagon content failures result from overburdened workers, a lack of materials, or missing equipment. Wagon content failures are limited to the trade and task that they affect. Wagon handoff failures are failures that impact the turnover of a takt area from one trade to another; these may include quality defects or the prior trade being late to handoff the area. Wagon handoff failures impact the shift between trades or tasks, but do not impact the project and takt plan success as a whole. The last type of failure defined by Lehtovaara et al. (2022) is a takt train failure. Takt train failures impact the whole project; this may include significant scheduling and coordination errors or compounding delays in wagon handoffs. Each failure may lead to a further failure, thus the FMEA framework aims to resolve takt planning failures before they cause a takt plan to fail. If the FMEA framework proves effective in categorizing takt plan failures, the rest of the steps outlined by Lehtovaara et al. (2022) can be applied to a takt plan. The FMEA framework has the potential to greatly decrease takt plan failures and therefore increase takt plan success.

The research was guided by the hypothesis that the FMEA-takt plan network will cover all identified types of failures within a takt plan. This paper applies the FMEA framework for identifying types of failures in a takt plan outlined by Lehtovaara et al. (2022) to a large scale, repetitive project, with the goal of determining the effectiveness of the framework in classifying failures within a takted project. The FMEA-takt plan framework has not been tested empirically. This paper seeks to begin the process of testing the FMEA framework by determining whether failures in a takt plan case study project fit the failure categories proposed by the FMEA framework.

LITERATURE REVIEW

TAKT TIME PLANNING

Takt time is often associated with the manufacturing industry, however its use in the construction industry dates back to the construction of the Empire State Building (Frandson et al., 2013). Its goal is to produce based on customer demand or the desired time frame of the customer (Haghsheno et al., 2016; Hopp & Spearman, 2008). It has proven more difficult to apply takt to construction than manufacturing for a variety of reasons. Most notably, construction happens on a much larger scale. For takt, construction may be considered a form of low-volume high-variety manufacturing so the takt time is typically a few days or one week as opposed to one minute (Ricondo Iriondo et al., 2016; Tommelein et al., 2022). Takt can be revolutionary since it increases both flow and transparency. Increasing flow and transparency levels the playing field on site or prioritizes all the contractors and trades equally and gives them equal opportunity to complete their work effectively (Koskela, 1992). Although similar to other methods that increase flow (LPS, LBMS), takt differs because it focuses on creating capacity buffers and decreases variability by providing consistency in turnover rates (Ballard, 2000; Seppanen & Kankainen, 2004; Tommelein et al., 2020). Frandson et al. (2013) proposed a method for planning and production control, takt planning. Takt planning allows takt to be applied to construction systematically.

Case studies have supported the value of takt planning as a method for construction production planning and control. Apgar et al. (2022) found that takt planning reduced planned and actual construction durations up to ~70% of the total workdays. A similar case study with a large, repetitive style project concluded that takt planning reduced project duration by 50% (Yassine et al., 2014). Binninger et al. (2018) conducted a case study and came to the same conclusion: takt planning significantly decreases construction duration. Even in cases where the takt was lost by the end of the project, takt planning decreased project cost, increased quality, and decreased throughput times (Alhava et al., 2019). In addition, takt aids in creating flow in the construction process, specifically within the trades (Kujansuu et al., 2020). However, despite these studies demonstrating the effectiveness of takt planning, further research is needed. Takt planning applies to the construction process with the goal of continuous improvements. More research should be conducted with a focus on how continuous improvements can be made to takt plans during the construction process (Lehtovaara et al., 2020).

FAILURES IN TAKT PLANS

Variability has always been at the forefront of research in lean construction since it is the enemy of reliability and productivity. For example, Tommelein et al. (1999) presented the Parade Game to teach students (and others) about the impact variability within and between trades has on the timeline of a project. The Parade Game effects teaches about variability in construction since it shows how having an inconsistent turnover rate frequently results in delays or other problems (Tommelein et al., 1999). Flow systems, such as takt plans, seek to create consistent turnover rates. However, this does not mean there is no variability in flow systems. Variability leads to failures; research into takt plan failures is research into variability. There is a lack of research regarding failures in flow systems, but other literature discusses reasons behind failures in scheduling. Some of these reasons include ignorance, weather, unique project nature, and lack of belief in scheduling methods among workers and management (Iyer et al., 2006; Muhammad et al., 2020). Weather is a common cause for scheduling failures in projects in the United States (Liu et al., 2021).

Research on takt planning investigates methods for preventing failures or reacting to failures but few apply these theories to case studies. Dlouhy et al. (2016) explored project management through a related method for production control, takt planning takt control (TPTC), that follows the project past the production stage. Application of TPTC resulted in a case study project reducing their construction time from eleven months to five months (Dlouhy et al., 2016). A recent case study described how unreliable workflow leads to greater waste by preventing the greatest possible production capacity and that increased transparency prevents delays (Dahlberg et al., 2021). Although takt plans result in greater construction efficiency, due to takt plan failures, the takt plans often take longer than planned. Real construction rates are approximately 20% slower than what is planned (Binninger et al., 2019). Dahlberg et al. (2021) proposed that weekly meetings and daily huddles are proactive steps to decreasing failures in takt planning. Binninger et al. (2017) identified 31 adjustment measures to increase flexibility in takt planning and decrease the impact of failure on the project. Most recently, Lehtovaara et al. (2022) applied FMEA methods to takt planning to better classify and proactively counter failures. Further understanding of failures in takt planning in practice is necessary for better scheduling and for improvements in project control systems such as takt planning, LBMS, and LPS (Ballard, 2000; Lehtovaara et al., 2022; Seppanen & Kankainen, 2004).

As presented by Lehtovaara et al. (2022), the FMEA method can be applied to takt planning to follow the takt plan through its lifespan and help with continuous production control and decreasing failure frequency. This is not the first time that FMEA has been applied to construction planning methods; FMEA was explored in construction in relation to the Last Planner System (Wehbe & Hamzeh, 2013). However, a detailed understanding of FMEA's utility in construction has yet to be realized. FMEA's usefulness has been demonstrated in other industries such as medicine and manufacturing (Bahrami et al., 2012). FMEA works well with takt planning since FMEA aims to result in action before any failures occur and takt planning increases transparency to enable improvement in the takt plan throughout construction (Bahrami et al., 2012; Lehtovaara et al., 2022).

METHODOLOGY

CASE STUDY

A case study was conducted to assess the applicability of the takt planning FMEA framework as outlined by Lehtovaara et al. (2022). Applying the FMEA-takt plan network to a case study project, bridges the gap between the theoretical and practical value of FMEA in takt planning. Not only is a case study a valid method for determining the validity of the FMEA takt planning framework, but in general case studies are valuable because they allow theories to be studied in their natural environment, possibly revealing new information that would remain undiscovered otherwise (Crowe et al., 2011). This case study was conducted using data from one project; Hartmann et al. (2008) demonstrate how a single case study has been used as an effective research methodology. Additionally, Lehtovaara et al. (2022) specifically call for validation of their theories via case studies and more in-depth research about failures within takt plans via case studies. This paper seeks to fill both research gaps.

The case study for this project followed a large data center project in Utah, USA, where five large data centers have been constructed, three of them being planned and scheduled using a takt planning system (Apgar et al., 2022). The case study project implemented a takt time of one day to enable a quicker throughput and a higher level of detail in the planning stage of the project (Apgar et al., 2022). Figure 1 shows a takt plan used in the case study project. Each row on the schedule corresponds to a workday and each row to a project work area. It is important to note that although a takt of one day was chosen, depending on the task, some trades worked in the same area for more than one day. The takt time was maintained by highly detailed schedules working to maintain a consistent beat despite this fact. In addition, the case study implemented pieces of the Last Planner System, such as Weekly Work Plans (WWPs), to guide the focus on pull planning during schedule creation (Ballard, 2000).

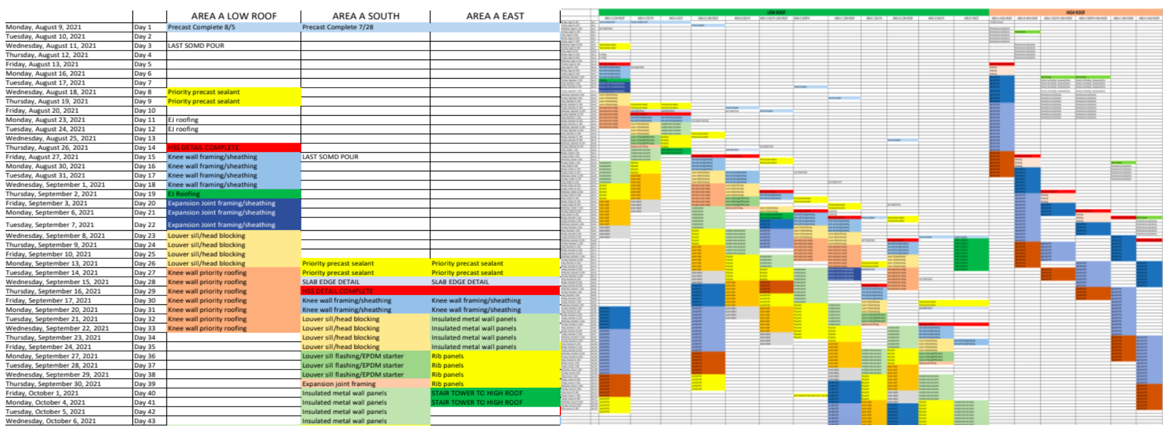

Figure 1: Takt Plan (with takt of one day)

APPROACH TO DATA COLLECTION AND ANALYSIS

Data was pulled from Weekly Work Plans (WWPs) for three of the five buildings in the case study. Since takt planning was implemented halfway through the construction process, data only exists for part of the project, however due to the size of the project, extensive data was collected on takt plan failures. Using the WWPs, they applied continuous production control by marking every failure in the takt plan and assigning a reason for the failure. Through observation of common causes of takt plan failure, the flow managers identified sixteen causes for failures within the takt plan and each failure was placed in one of those categories. The WWPs were available for data collection and analysis for half of Building 3, and all of Building 5 and Building 6. Six months of WWPs were available for data collection and analysis for Building 3 whereas Building 5 and Building 6 both had over one year's worth of WWPs to pull from. Each failure in the takt plan was gathered from the WWPs and then compared with the FMEA framework outlined by Lehtovaara et al. (2022) with the goal of determining whether the proposed FMEA framework describes all documented causes for failure in the case study takt plan. Despite unequal data for each building, sufficient data was collected to determine the trends of the data. The number of takt plan failures for each failure identified in the case study was summed based on the failure category as well as the total number of failures for the building. Trends in the data are identified and possible explanations for the trends are discussed, such as the impact of a learning period after the implementation of a takt plan (on both planning and production sides).

FINDINGS AND DISCUSSION

DATA AND ANALYSIS

For each week in the WWPs, failures in the takt plan were identified by the superintendents, along with their associated reason for failure. Takt plan failures were only identified when the task would not finish on time. Therefore, the number of failures in the takt plan was not heavily impacted by the project having a takt time of one day. During data analysis both the task that didn't follow the takt plan and their reason for failure was pulled from the WWPs. Then the failures (called variances in the case study WWPs) were organized into the failure categories outlined in the FMEA-takt plan framework proposed by Lehtovaara et al. (2022). In the case study project, the flow managers identified sixteen types of failures that occurred in the takt plan. Notably, the failures include both administrative failures that impact construction tasks such as submittals, trade failures such as failed inspections, and logistical failures such as missing materials and equipment. The identified failures and number of each failure for Building 3 are shown in Table 1. Table 1 also correlates each failure identified in the case study to a FMEA takt plan failure.

An additional FMEA takt plan failure was added, titled 'other', that contains failures identified in the case study that don't correlate to any of the three FMEA takt plan failures. This category includes takt plan failures due to weather, unforeseen conditions, COVID, and unknown reasons (i.e., failures that are outside the control of a takt plan or uncontrollable in nature). This last type of failure was added by the researcher to describe the failures marked in the WWPs for which no distinction of reason for takt plan failure was given. Any number with an asterisk next to it (*) indicates that failure in the case study could fall into more than one FMEA takt plan failure category. Four of the case study failures fit this description: client change (it is assigned to wagon handoff but could be in the 'other' category because it is not directly part of the scheduled takt plan), submittals (same as client change), contracts (same as client change), and finished late (could result in a takt train failure). It was debated where the administrative tasks fit in the FMEA framework (client change, submittals, and contracts), however they were ultimately placed under wagon handoff because the takt plan methodology can be applied to all project aspects, not just physical construction. Further investigation into how a takt plan may be applied to all aspects of a project would be worthwhile in order to better understand all the factors that make a takt plan successful.

Table 1: Building 3 FMEA and Failure Classification

	Types of Failures			
Variances	**Wagon Content**	**Wagon Handoff**	**Takt Train**	**Other**
Client Change	-	0*	-	-
Submittals	-	0*	-	-
Arch/Eng/Design	-	-	4	-
Contracts	-	0*	-	-
Materials Not Available	42	-	-	-
Equipment/Lift Not Available	2	-	-	-
Labor Not Available	125	-	-	-
Prior Work Not Complete - Others	-	125	-	-
Prior Work Not Complete - Self	23	-	-	-
Schedule/Coordination	-	-	70	-
Weather	-	-	-	37
Unforeseen Conditions	-	-	-	16
Finished Early	-	26	-	-
Finished Late	-	9*	-	-
COVID	-	-	-	0
Unknown	-	-	-	2
Failed Inspection	-	1	-	-
Totals for Each Failure Type	**192**	**161**	**74**	**55**

For Building 3, wagon content failures account for the largest reason for takt plan failure, with *Labor Not Available* being the largest addition to the wagon content failures. The case study had construction spanning over large portions of COVID-impacted time, and therefore during a time of labor shortage in the United States. A case study conducted in a different time or place likely would not have *Labor Not Available* as the largest wagon content failure. *Prior Work Not Complete – Others* ties with *Labor Not Available*, accounting for 125 takt plan failures; this type of failure falls under wagon handoff and demonstrates how unreliability is still prevalent in takt plans as well as the importance of continuous improvement in takt planning.

Building 5 (shown in Table 2) was analyzed in the same way, however, results were very different. Takt planning was applied to construction midway through the construction of Building 3, and only six months of data was collected for Building 3. Building 5 was the first building that used takt planning for its entire construction, resulting in a much high number of variances or failures marked in the WWPs. Building 5 had approximately 2400 takt plan failures with 1/3 of them lacking a reason for failure (*Unknown*). This can be due to a variety of reasons, such as a lack of awareness of how to use the WWPs and the takt planning system and/or a lack of dedication on part of the superintendents to the takt plan. Therefore, the 'other' FMEA failure category is responsible for the greatest number of failures in the takt plan for Building 5. However, the second and third most common reasons for takt plan failure are *Labor Not*

Available and *Prior Work Not Complete – Others*, respectively. Building 3 was not unique in having a high percentage of takt plan failures due to *Labor Not Available* and *Prior Work Not Complete – Others.*

Table 2: Building 5 FMEA and Failure Classification

	Types of Failures			
Variances	**Wagon Content**	**Wagon Handoff**	**Takt Train**	**Other**
Client Change	-	14*	-	-
Submittals	-	4*	-	-
Arch/Eng/Design	-	-	26	-
Contracts	-	8*	-	-
Materials Not Available	122	-	-	-
Equipment/Lift Not Available	19	-	-	-
Labor Not Available	363	-	-	-
Prior Work Not Complete - Others	-	313	-	-
Prior Work Not Complete - Self	68	-	-	-
Schedule/Coordination	-	-	131	-
Weather	-	-	-	141
Unforeseen Conditions	-	-	-	200
Finished Early	-	56	-	-
Finished Late	-	118*	-	-
COVID	-	-	-	22
Unknown	-	-	-	851
Failed Inspection	-	35	-	-
Totals for Each Failure Type	**572**	**548**	**157**	**1214**

Analysis of data from Building 6 (Table 3) shows similar results with *Prior Work Not Complete - Others* as the top reason for takt plan failure and *Labor Not Available* as the second most prevalent reason for failure. For Building 6, the FMEA category that accounts for the highest number of takt plan failures is ‘other’ due to the large amounts of *Unknown* failures. However, the number of failures identified as *Unknown* decreased dramatically between Building 5 and Building 6. This shows the learning associated with the implementation of takt plan and reflects their efforts to use production control (Seppanen et al., 2004). Another difference from Building 5 is that the second highest FMEA failure category was wagon handoff as opposed to wagon content. This also shows learning on the part of the flow managers since they were able to better supply the materials necessary for construction. This is possibly due to outside factors, however for Building 6, failures due to wagon content errors is significantly less that failures due to wagon handoff.

Table 3: Building 6 FMEA and Failure Classification

	Types of Failures			
Variances	**Wagon Content**	**Wagon Handoff**	**Takt Train**	**Other**
Client Change	-	11*	-	-
Submittals	-	2*	-	-
Arch/Eng/Design	-	-	22	-
Contracts	-	5*	-	-
Materials Not Available	69	-	-	-
Equipment/Lift Not Available	20	-	-	-
Labor Not Available	222	-	-	-
Prior Work Not Complete - Others	-	351	-	-
Prior Work Not Complete - Self	77	-	-	-
Schedule/Coordination	-	-	185	-
Weather	-	-	-	146
Unforeseen Conditions	-	-	-	167
Finished Early	-	86	-	-
Finished Late	-	100*	-	-
COVID	-	-	-	10
Unknown	-	-	-	329
Failed Inspection	-	25	-	-
Totals for Each Failure Type	**388**	**580**	**207**	**652**

DISCUSSION

The FMEA framework proved mostly effective in separating takt plan failures into correct categories. However, an additional 'other' category was necessary to account for conditions that cannot be controlled by takt planning, and to note the human error that occurred in documenting takt plan failures. This reflects what Binninger et al. (2019) found, that outside forces are major components in whether the takt plan follows the proposed schedule or not. Therefore, the FMEA framework for takt should be altered to account for these 'other' failures to improve effective application to takt projects in general.

The *Unknown* failures are important to note since they show that accurate documentation and reporting of variances from the schedule can influence an understanding of which failures are most prevalent. In addition, they show that without complete dedication on part of the superintendents to document failure information on the takt plan, FMEA may be harder to apply. Lehtovaara et al. (2020) list "social integration" as a key step to better takt planning implementation. To effectively use FMEA in conjunction with takt planning, the system must be socially integrated. In the case study, there were multiple superintendents and flow managers that worked to enable takt planning to be carried out on such a large project, yet, despite their best efforts, there was still significant human error that led to inadequate data collection. Therefore, it must be noted that successful takt plan application reflects whether the management teams and contractors are willing to put in the additional administrative work.

The amount of data and specifically the amount of clearly labeled takt plan failures across the three buildings shows learning on part of the project team. As they better learned to use the takt planning system and WWPs, more failures were identified, and more were recorded with an associated reason for failure. Building 3 has an artificially low number of failures as compared to the other buildings since the takt plan was not applied until halfway through construction. The project team also likely did not record all the variances that occurred in the takt plan because they were still learning how to work the new scheduling system. However, the volume of data enables some trends to be identified. The number of recorded failures jumped up dramatically with Building 5 due to the fact that they were more diligent in marking the variances from the schedule and that data was recorded for the entirety of the building's construction. A high number of *Unknown* failures was present reflecting the learning of the superintendents. Building 6 saw a decrease in both the number of *Unknown* takt plan failures and the total number of failures. The decrease in takt plan failures show continuous improvement, reflecting the goal of flow and lean construction (Koskela, 1992). Takt plans work but take production control to be effective. Between Buildings 5 and 6, the number of wagon content failures dropped significantly. The team worked to prevent wagon content failures as the project progressed. This resulted in a significant decrease in construction duration between the two buildings (Apgar et al., 2022). In fact, Apgar et al. (2022) found that there was approximately a 70% decrease in the total number of workdays required for roofing construction. However, the number of wagon handoff failures increased. An assumption may be made that if the project were to continue and more buildings were constructed and their failures analyzed, improvements would be made in wagon handoffs and the total number of takt plan failures would continue to drop.

Limitations to the study include the fact that the project was done on a case study, the study was done on a project not using the FMEA framework, and limited communication was available between the researchers and the project team. Although case studies are valuable to understand theory as it exists in practice, it is important to note that the results from the study are specific to the project. This project was a large scale, repetitive project that implemented takt planning halfway through. Other projects may have very different results due to size, project nature, and method for takt plan implementation. The case study project did not use the FMEA framework, so failures in the takt plan were classified according to the project flow team. It is important to note that since the FMEA framework wasn't used, the researchers were unable to analyze the full impacts of FMEA on a project. In a project where FMEA has been fully applied, continuous improvements are made as failures are identified to improve project performance over time. However, the purpose of the study was to determine whether the FMEA-takt plan framework addressed all the failures that exist in a takt plan. The project goal was achieved but the project must be understood in context. Limited communication prevented the researchers from understanding more about some of the failure categories designated by the lean innovation team on the job site. Using intuition and available resources on the WWPs, the researchers fit the project failures into the FMEA-takt plan failure categories as best as possible. Many of the failure categories given in the project, however, were self-explanatory or easy to infer context for due to notes in the WWPs. Therefore, despite limitations, the case study effectively increased an understanding of how failures exist in takt plans and how they might fit into a FMEA framework.

CONCLUSIONS

The purpose of this paper was to serve as a case study to test the validity of the failure types identified by Lehtovaara et al. (2022) in their proposed FMEA-takt plan framework. Collected data and analysis demonstrate that although the framework works for most failures in a takt plan, another category should be added to account for the failures that are beyond the scope of the takt plan or outside of normal causes for failure within a takt plan. These include failures such as *COVID*, *Unforeseen Conditions*, and *Unknown* failures. Although possibly not true for every project, *Unknown* failures should be expected since not all failure may be documented correctly nor fit into a specific failure category. This is not to say the rest of the FMEA-takt plan framework is not applicable or that it could not be altered slightly to fit all types of failures that occur in a project with a takt plan. The purpose of the study was to determine whether the proposed failure categories might work for a real project. The study demonstrated the learning that is associated with takt plan implementation on a large scale, repetitive project. As the project team learns the takt plan production control method, takt plan failures decrease.

An additional insight the researchers gathered while conducting the study was that some takt plan failures result from administrative decisions. The researchers chose to sort those failures into wagon handoff failures. However, since administrative decisions exist above the scope of a takt plan, they could also fit into 'other' failures. This allowed for the insight that it may be valuable to apply takt planning to all processes that exist within a project, not just the construction process.

Further research should be done to follow the proposed FMEA-takt plan framework through the lifecycle of a project (Lehtovaara et al., 2022). Research should also be done on other projects to discover whether certain failures are more prevalent takt plans than others or if they are completely project dependent. Additionally, further research should be completed to understand the relationships between failures and whether seasons, trades, or areas in the world are more predisposed to a certain failure than another.

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RESULTS OF THE CAUSES AND IMPACTS OF MAKING-DO WASTES IN PRODUCTION IN FORTALEZA, CEARÁ, BRAZIL

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ABSTRACT

This report aims to present the possible relationships between the prerequisites, categories, and impacts of *making-do* wastes from the non-conformity data provided by the Quizquality of six companies participating in INOVACON. From the analysis of the missing prerequisites related to the city of Fortaleza, it was possible to see that labor (52.75%), materials and components (26.69%), and interdependent tasks (5.90%) presented the most associated wastes. The main categories related to wastes are component adjustments (53.84%), sequencing (21.01%), and storage (9.76%). The highlighted prerequisite information for the Goiania cases was motivated by the absence of projects, blueprints, studies, or procedures that should provide necessary information to execute work packages which were unavailable, unclear, and/or incomplete. Based on these results, the determined actions are the need to improve information management to cooperate so that there are no errors arising from incomplete projects or difficulty in passing on necessary information to the employees responsible for performing the service/work.

KEYWORDS

Making-do, prerequisites, categories, impacts and work packages.

INTRODUCTION

It is a common goal among the academic and technical communities to make the construction industry more competitive. To this end, it becomes necessary to increase controls at all project stages and to increase the performance of processes and products, as well as to reduce

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production, material wastes, and impacts on the environment (ADEWUYI, IDORO and IKPO, 2014; ANSAH, SOROOSHIAN and MUSTAFA, 2016).

Thus, companies have developed actions that provide improvements in construction processes to avoid the occurrence of failures, losses, accidents, and/or rework, thereby ensuring improvements at the organizational level, cost reduction, meeting deadlines, minimizing errors, as well as in quality and productivity. Studies conducted in different countries indicate that losses in construction represent a relatively high percentage of production costs (FORMOSO et al., 2002; FORMOSO et al. 2017; HWANG et al., 2009; KOUSHKI, KARTAM, 2004; LOVE, LI, 2000; LEÃO, 2014; LEÃO et al., 2016). High production costs are related to losses throughout the construction processes and should be understood as any inefficiency in the use of equipment, materials, labor, and capital (VIANA; FORMOSO; KALSAAS, 2012).

Moreover, productivity is a constant concern for any construction company in the current landscape of the construction industry to establish itself in the market competitively. Companies face great competition due to increasing demands from customers who want products with adequate quality and satisfactory performance. Nevertheless, management strategies have been adopted by construction companies to improve organizational and construction performance. In this sense, the implementation of lean construction based on the Toyota Production System (TPS) and Total Quality becomes an answer to the culture of improvisation in construction sites and can be proven by several implementations around the world.

Toyota created a loss classification aimed at making wastes visible and facilitating identification of their causes to foster a "zero waste" culture among its employees called the "Seven Wastes" (Shingo, 1989). According to Ohno (1988), waste or loss refers to all production resources which only increase costs and do not add value to the product, explained through the seven major categories of wastes adopted by the STP.

Soilbelman (1993) states that the reduction of wastes must consider that there is an acceptable level of wastes, which can only be reduced through significant changes in the level of technological and managerial development of the company. Accordingly, the referred author classifies wastes as unavoidable (or natural waste) and avoidable, in which the occurrence costs are substantially higher than the prevention costs. Thus, several theories arise or evolve in this context. However, it is known that an important increment for lean construction was the designation by Koskela (2004) of a new category of wastes called making-do, added to the widely known and applied list of Ohno (1988) and Shingo (1989).

THEORETICAL REFERENCE

The terms unfinished work, work in progress, buffer, rework, work completion, and work stoppage have been reconceptualized in a trajectory of lean history to be associated with making-do. Nevertheless, it is important to note that these terms already existed before the evolution of lean construction theory. Likewise, Ronen (1992) and Koskela (2000) already presented the theoretical basis for the making-do in their works, highlighting that the latter was based on the former to establish the complete kit (prerequisites to perform a certain task). Koskela, Bolviken, and Rooke (2013) point out making-do as a central waste in construction for being the possible main cause of other wastes.

Since then, studies related to ways to use the concept of making-do loss to minimize or eliminate activities which do not add value to the process have been developed, either in various stages of the life cycle (from project conception to maintenance), such as in: project preparation (Koskela et al., 1996; Grosskopf; Menezes; Santos, 2004; Neve; Wandahl, 2018); construction site logistics (Ghanem et al., 2018, Perez et al., 2015); the supply chain (Taggart, Koskela, and Rooke, 2014); production slack (Fireman, Saurin, and Formoso, 2018); developing or augmenting methods or tools, virtual or otherwise, to facilitate the identification of these wastes (Sommer, 2010, Fireman, 2012, Leão; Formoso; Isatto, 2016); or by identifying other wastes in a cause and consequence discussion concerning making-do waste (Koskela et al., 2019; Formoso et al., 2011; Fireman; Formoso; Isatto, 2013; Santos; Santos, 2017; Pérez, Costa, and Gonçalves, 2016; Pérez; Costa, 2018).

Several studies have been conducted seeking to identify the causes and effects of making-do waste in construction, notably those by Sommer (2010) and Fireman (2012). However, few works are dedicated to identifying specific cause-effect relationships associated with this type of waste. In one such study, Spohr and Isatto (2018) argue that the associations between causes and effects of making-do are quite diverse, with some being very close and central, while others are quite diverse and peripheral, suggesting that managerial attention aimed at reducing making-do wastes should focus on a more central set of effects. However, due to the small number of cases studied, the results obtained in that study do not enable a broader generalization to identify the associations between each of the causes and effects individually considered, or specific mechanisms which govern such relationships, pointing out a gap to be explored.

According to Koskela (2004), making-do waste occurs when a job site activity is started without having all the necessary prerequisites, or when its execution continues even if one or more prerequisites are no longer available. Ronen (1992) called this set of prerequisites a complete kit and states that there are two consequences, technical and behavioral. In addition to these consequences, Koskela (2004) added the safety waste caused by making-do; this safety waste is the result of abnormal manufacturing conditions.

The waste identification method proposed by Sommer (2010), and then complemented by Fireman et al. (2013) and Santos and Santos (2017), presents three groups. The first is used to identify missing prerequisites in work packages, the second is to identify the most affected waste categories, and the last assesses the impacts of waste.

Next, the work packages to be executed are defined in planning, and making-do wastes are identified when there are no working conditions, and therefore alternatives or improvisations are used so that the work is not interrupted. The method application must consider that these wastes may or may not generate some impact on production, not jeopardizing the execution of the packages. Therefore, it is necessary to first identify which activities can lead to these or other wastes in the production process (SOMMER, 2010).

It is noteworthy that wastes by making-do can occur in different ways, and there are numerous possible combinations of prerequisites, categories, and impacts in the construction environment. Some authors have highlighted that improvisations are present in all of the construction site stages, thereby making it difficult to identify and avoid them, and requiring strict control of construction processes, investments in cultural change conducive to improvisation and standardization (AMARAL et al., 2019; SANTOS et al., 2020, FORMOSO et al., 2002; JOSEPHSON; HAMMARLUND, 1999; HORMAN; KENLEY, 2005; FORMOSO et al., 2017; OHNO, 1997). Moreover, some authors reported difficulties in identifying and classifying making-do wastes, pointing to the need to improve the methods used. In addition, the need to develop more quantitative analyses and the acceptable limits of making-do wastes is also highlighted in the literature by several authors (SAURIN; SANCHES, 2014; AMARAL et al., 2019; SANTOS et al., 2020, JOSEPHSON; HAMMARLUND, 1999; HORMAN; KENLEY, 2005; FORMOSO et al., 2002; FORMOSO et al., 2011; FORMOSO et al., 2015; FORMOSO et al., 2017; FORMOSO et al., 2019; LEÃO, 2014; FIREMAN & FORMOSO, 2013; and KALSAAS, 2012).

On the other hand, it is noteworthy that only surveying making-do wastes does not provide enough information for the manager to completely prevent these wastes from occurring in their next undertaking or task. The targeted analysis of impacts is also important to facilitate feedback to the manager, as it allows the manager to prioritize the necessary corrections toward the most efficient work possible.

Leão et al. (2014), Formoso et al. (2015), Fireman et al. (2013), Saurin and Sanches (2014), and Kalsaas (2012) reported difficulties in identifying and classifying making-do wastes, pointing out the need to improve the methods used and develop more quantitative analyses and the acceptable limits of making-do wastes, as well as highlighting the need to prioritize decision-making by the manager; this means instead of the manager concentrating their efforts to correct all the intercurrences identified on-site, they may concentrate energy, resources, and management on the stages that contribute greater impact to achieve better results in the most critical points of the work concerning making-do.

OBJECTIVE

This report aims to present the possible relationships between the prerequisites, categories, and impacts of making-do wastes from the non-conformity data provided by the Quizquality of six companies participating in Civil Construction Industry Innovation Program (INOVACON).

METHOD

Table 01 characterizes the companies participating in these analyses. The group of companies defined in the sample are part of the INOVACON and subsidized this survey stage.

Table 1: Characterization of the construction companies.

Company Code	Code Work	Description	Current Phase Execution	Total Employment Area (m²)	Nr. of Floors
M	M-E1	Medium standard residential building - 3 towers	Concluded	9,444.6	23
N	N-E1	High Standard Vertical Residential Condominium - 2 towers	Running	2,860.0	15
	N-E2	High-end Vertical Residential Building	Running	2,390.0	19
	N-E3	High-end Vertical Residential Building	Running	2,480.0	30
O	O-E1	Low-rise residential building - 11 towers	Running	18,700.0	4
	O-E2	Medium standard residential building - 3 towers	Running	12,200.0	7
P	P-E1	Low-rise residential building - 11 towers	Running	26,145.0	5
Q	Q-E1	High-end Vertical Residential Building	Running	2,420.0	23
R	R-E1	High-end Vertical Residential Building	Running	2,350.0	20

IMPLEMENTATION STEPS

The research steps are detailed below.

Step 1: Definition of protocol for identifying making-do wastes.

Protocols for data collection were proposed based on previous studies. The causes, categories and impacts for making-do wastes were defined. The wastes were classified according to the steps and sub-steps following the NBR 12721 presets (ABNT, 2005). The impacts were classified according to the adopted parameters of reduced productivity, lack of motivation, loss of material, rework, reduced safety, reduced quality, and lack of finishing (RONEN, 1992; KOSKELA, 2004; FIREMAN et al., 2013).

Step 2: Diagnosis performed in Fortaleza/CE/Brazil based on the export of QuizQuality.

Preliminary analyzes of a database with 156,762 compliance and non-compliance data from the companies were conducted. From the 8,842 non-conformities analyzed, 6,339 instances of data were classified. The analysis period covered the years 2020 to 2022. The data refer to seven construction companies from Ceará, using data stored in the QuizQuality management platform, developed by the company Aval Engenharia.

Step 3: Dashboard enhancement for analysis of interactions between parameters.

The data were integrated into Microsoft Power BI® and the analyzed parameters were chosen based on the information classification on wastes, being divided into eight items related to prerequisites, eight to categories and seven to impacts (Table 2). Then, the parameters from this group (presented in Table 02) which highlighted the information were chosen to obtain a more specific and detailed analysis of the database.

Table 2: Parameters analyzed for making-do wastes.

Prerequisite	**Categories**	**Impacts**
Information	Access/mobility	Decreased productivity
Materials and component	Component adjustments	Demotivation
Labor	Workspace	Loss of material
Equipment or Tools	Storage	Rework
Space	Equipment/Tools	Security reduction
Interdependent tasks	Temporary installations	Quality reduction
External conditions	Protection (security)	Lack of finishing
Temporary installations	Sequencing	

Source: The authors.

The distribution of wastes by making-do could be interpreted by the hierarchical tree diagram graphs with the analysis carried out in Microsoft Power BI® (Figure 1), and the counting of wastes from this analysis can be sequentially analyzed from the prerequisites, categories and impacts of these, thus enabling to identify which prerequisites have the greatest influence on the occurrence of wastes.

The graphic representations chosen for data analysis were: hierarchical tree (to obtain a Diagram with the relations between the wastes by prerequisites, categories, and impacts), funnel (to analyze the construction stages and their relationships with the teams of works with the highest occurrence of wastes) and ranges (to identify the relationships between the chosen parameters, and how the prerequisites, categories and impacts interacted with the database), as they better present the analyzed results.

The 156,762 compliance and non-compliance data from the companies were analyzed according to the distribution shown in Table 3. From the 8,842 non-conformities analyzed, 6,339 instances of data were classified. The reduction of the database for the classified data is justified by the absence of response or inconclusive answers for the Quizquality fields: "characteristic description", "problem response" and "correction action response", making it impossible to classify the data according to the spreadsheet used by the research group. Table 4 shows three cases that make it impossible to tabulate the data.

Table 3: Database extracted from QuizQuality.

Company	**Database**	**Analyzed Data**		**Classified Data**	
M	63,618	6,367	10.01%	4,770	7.50%
N	63,601	1,887	2.97%	1,077	1.69%
O	26,923	512	1.90%	460	1.71%
P	41	41	100%	15	36.59%
Q	34	34	100%	17	50%
R	2,545	1	0.04%	0	0%
	156,762	**8,842**	**5.64%**	**6,339**	**4.04%**

Table 4: Examples from the analyzed database that were not classified.

Item	Feature Description	Problem Answer	Response Action Containment
1	*Shafts* Compartmentalization with drains	Locked Hydraulic *Shafts*	Not defined
2	Painting Walls and Frames - Stains	Room 01 - Stains on the wall	Repaint wall
3	Operation	Does not turn on	Repair

It was necessary to individually analyze each non-compliance provided by the companies to classify the data, which were subsequently tabulated in Microsoft Excel®. Then, a Microsoft Power BI® dashboard was developed from this data to provide an interactive data analysis and the parameters to be analyzed were chosen. These in turn were divided into eight items related to prerequisites, eight to categories, and seven to impacts for making-do wastes.

Step 05: Alignment meetings between partners.

Alignment meetings were held with all the companies participating in the study to present and discuss the results and analyzes, and to establish new theoretical frameworks aimed at reducing wastes in the production process, including new concepts and classifications about wastes.

TEAMS AND STEPS INVOLVED

The non-conformities found had a concentration of 54.33% of the data related to the coating and finishing stage, and 19.03% for installations and appliances, as shown in Table 05. It is believed that this percentage (54.33%) is related to the more complete recording of non-conformities in the final inspection stages, with repair needs for receiving the housing unit by the client since all the identified problems must be solved, thereby resulting in a greater recurrence of non-conformities described/detailed by the team involved in filling in this data.

Table 5: Wastes by classified stages.

Step	N.º	%
Coating and finishing	3,444	54.33%
Fixtures and fittings	1,206	19.03%
Structure	723	11.41%
Walls and panels	538	8.49%
Completion of the work	404	6.37%
Initial Services	22	0.35%
Covers and protections	2	0.03%
Total	**6,339**	**-**

Problems in the main stage of cladding and finishing were identified in the wooden doors, such as damage and malfunctions in the stops and jambs, requiring adjustments and/or replacement. Additional problems were identified in floor trims, malfunctions and/or changes in tone and/or the presence of stains on the ceramic tiles.

Regarding the teams involved, we conclude that the carpenter, bricklayer, tiler, janitor, plumber, and painting teams presented the most non-conformities, with 22.68%, 16.26%, 14.45%, 13.87%, 9.69%, and 8.69% respectively.

These teams were mainly related to the coating and finishing stages and to installations and appliances, suggesting a need for monitoring and training of these teams so that there is a reduction in these non-compliance occurrences.

ANALYSES OF THE PREREQUISITES, THE CATEGORIES, AND THE

IMPACTS OF MAKING-DO

From the analyses of non-conformities in the database, it was found that labor (52.75%) and materials and components (26.69%) were the prerequisites that showed the most associated wastes. The labor wastes were related to execution problems in the coating and finishing stages (57.12%), involving the mason (27.06%), carpenter (21.02%), and tiling (15.40%) teams, directly impacting the execution and completion of the services.

The wastes related to materials and components were linked to problems in the supply and use of the material, being associated with the "covering and finishing" (51.06%) and "installations and appliances" (16.84%) stages from applying non-compliant materials (e.g., damaged window frames; ceramic coating with stains or changes in tone), materials in insufficient quantities (i.e. electrical material), or materials with higher performance than those specified or requested in the project (i.e. steel).

The prerequisites of labor and materials and components were related to the highest impacts of rework (41.63%) and lack of completeness (33.27%), which are intrinsically related to the characteristics of the most recurrent stages (Figure 01).

The analysis of the non-conformities shows that labour, materials, and components are the main prerequisites related to the associated wastes, with 52.49% and 26.6%, respectively (Figure 01). The adjustment of components category can be understood as adjustments made on-site to speed up the service or simply adapt it to what should be done, justifying its relationship with the stages of "coverings and finishing" and "structure", corresponding to 42.31% and 19.87% of the cases identified, respectively, as well as "installations and appliances" and "panels", corresponding to 19.13% and 13.18% of the cases identified, respectively. The impact of this category on the structure, wall and panel stages occurs more frequently since the laborers end up making decisions on-site without consulting those responsible for their work.

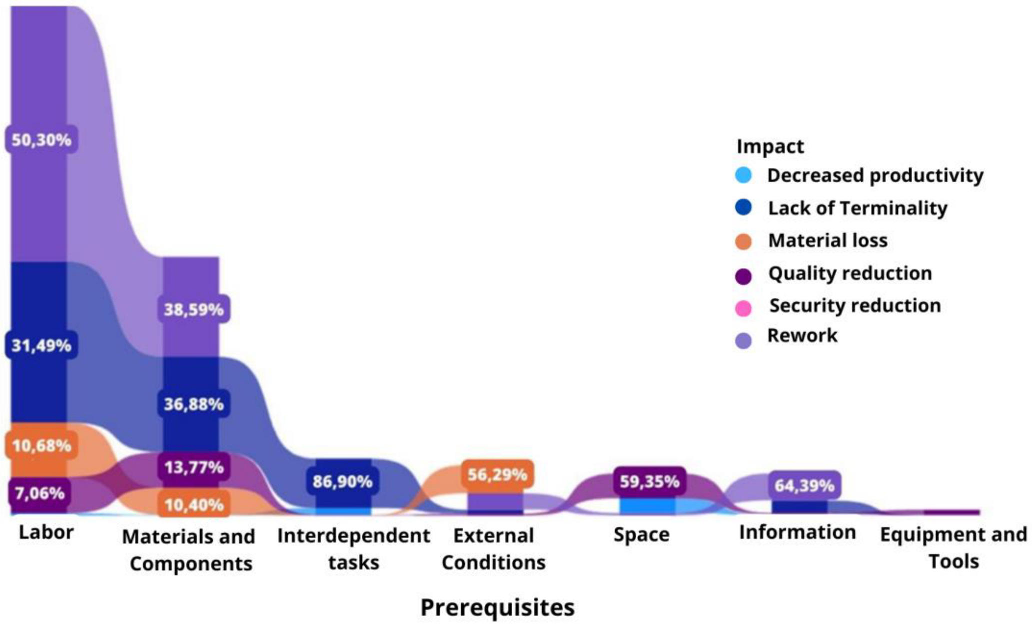

Figure 1: Correlation of wastes between prerequisites and impacts.

Next, the "sequencing" category has "coatings and finishing" (47.52%) as its main associated stage, and "lack of completeness" (70.12%), "rework" (19.07%), and "reduction in quality" (8.11%) as its main impacts. The main prerequisite regarding company "M" was labor (47.34%), followed by materials and components (31.97%) and external conditions (6.96%). The categories of greatest influence were component adjustments (44.03%), sequencing (23.94%), and storage (12.91%). The main impacts were in rework (39.12%), lack of completeness (33.48%), and material loss (12.52%).

The main prerequisite found when analyzing company "N" was labor (69.55%), followed by materials and components (11.42%) and interdependent tasks (9.66%). In addition, the categories of greatest influence were component adjustments (84.77%), sequencing (10.31%), and access/mobility (3.25%). The main impacts were rework (46.80%), lack of completeness (33.61%), and material waste (10.96%).

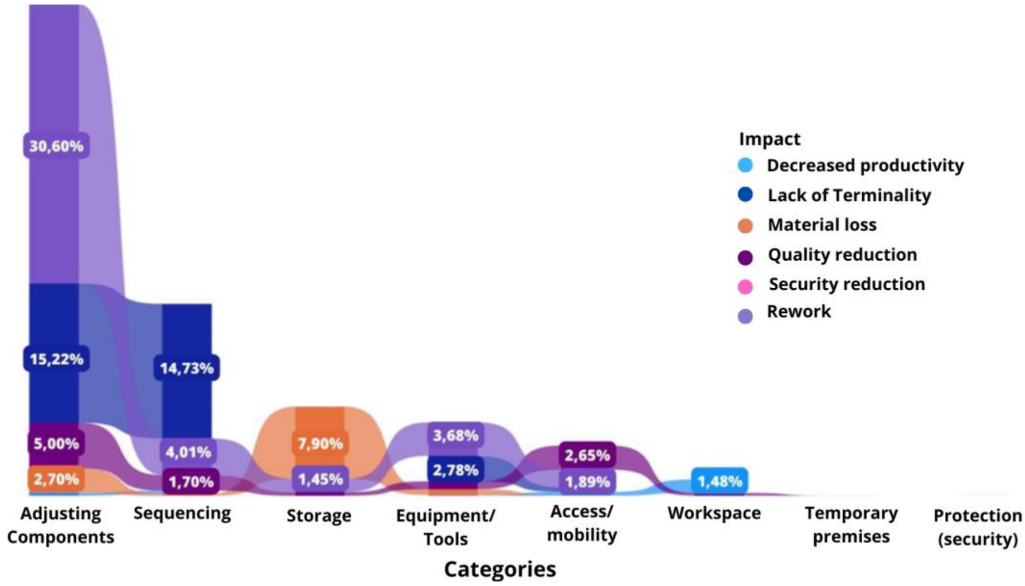

Figure 2: Correlation of wastes between categories and impacts.

The main prerequisite found for company "O" was labor (71.09%), followed by information (10.43%) and interdependent tasks (9.35%). In addition, the categories of greatest influence were component adjustments (81.96%), sequencing (15.65%), and work area (1.09%). The main impacts were rework (56.74%), lack of completeness (31.52%), and reduction in quality (8.04%). Next, the main prerequisite found by analyzing the data from company "P" was labor (33.33%), followed by materials and components (26.67%) and information (20.00%). Moreover, the categories of greatest influence were component adjustment (53.33%) and sequencing (46.67%). The main impacts were presented by rework (4.00%), lack of completeness (33.33%), and material waste (20.00%).

Next, the main prerequisite for company "Q" was equipment and tools (58.82%), followed by labor (29.41%) and materials and components (11.76%). The most influential categories were component adjustments (88.24%) and equipment/tools (11.76%), while the main impacts were presented by quality reduction (82.35%), rework (11.76%), and productivity decrease (5.88%).

From an overall perspective, it is concluded that the prerequisites of greatest influence among the companies are labor (52.75%), followed by materials and components (26.69%) and interdependent tasks (5.90%). Furthermore, the categories with the highest occurrence are related to component adjustments (53.84%), sequencing (21.01%), and storage (9.76%). The main impacts were rework (41.63%), lack of completeness (33.27%), and loss of material (11.50%).

DISCUSSION

The hierarchy diagram graph shows the relationships between the prerequisites, categories, and impacts. The center represents the total number of impacts recorded in the database, while the total value is highlighted in blue, and the quantities and lines under analysis are different from each other on both sides (Figure 3). In Figure 3, two diagrams are shown, split between the left and right-side diagrams, of the relationship between the prerequisites, categories, and impacts. The center represents the total number of impacts recorded in the database, while from the total value (center) the quantities and lines are highlighted in blue, which are different from each other for both sides.

From the analysis of the missing prerequisites related to the city of Fortaleza, it is possible to see that labor (52.75%), materials and components (26.69%), and interdependent tasks (5.90%) presented the most associated wastes. The main categories related to wastes are component adjustments (53.84%), sequencing (21.01%), and storage (9.76%). In addition, rework (41.63%), lack of finishing (33.27%), and material waste (11.50%) represent the main impacts related to wastes (Figure 3).

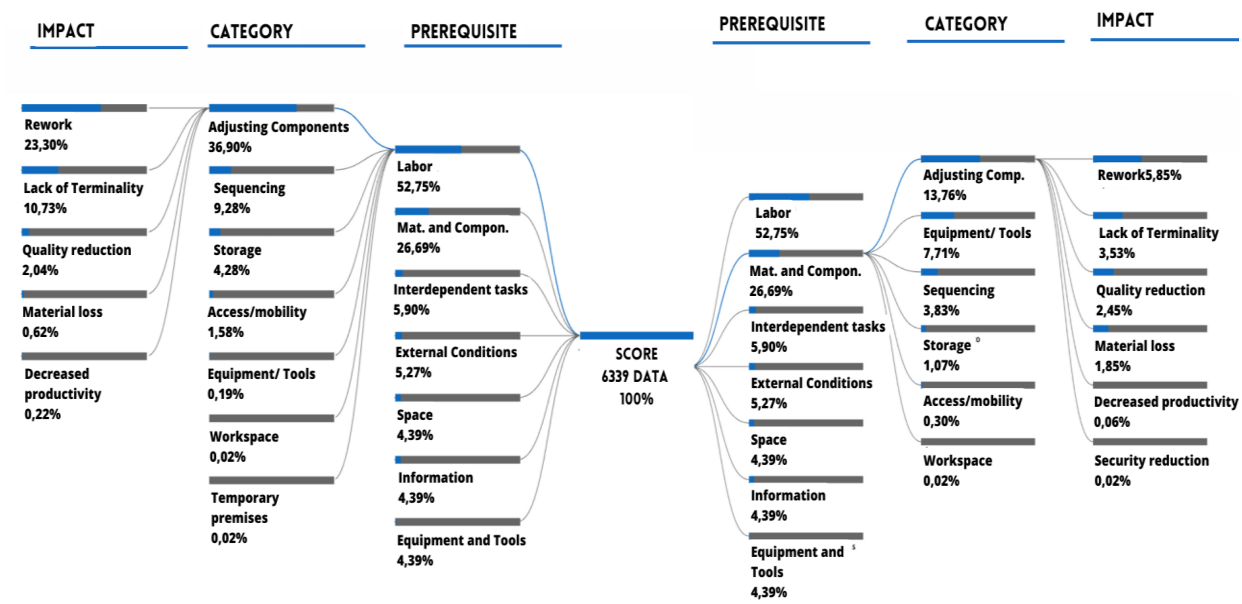

Figure 3: Diagram of the relations between wastes per prerequisite, category, and impacts - Fortaleza Results.

The teams involved in the analyses were: carpenter (22.68%), bricklayer (16.26%), tiler (14.45%), laborer (13.87%), plumber (9.69%), and painter (8.69%); while the percentages show the team that presented the highest non-conformities. Through these data, the labor prerequisite can be justified by its unavailability in terms of quantity and/or skills needed by the work teams, specifically the carpentry (22.68%), bricklayer (16.26%), and tiling (14.45%) teams, who contributed to the impact of wastes mainly related to rework. With this in mind, we suggest actions aimed at identifying the need for requalification, monitoring the services performed, the need for adequate dimensioning of the construction management, and better selection and supervision of the companies outsourced for the execution of the services.

CONCLUSION

The aim of this work was to identify associations between each of the causes and effects considered individually, or the mechanisms which direct such relationships; as a result, it is concluded that making-do wastes can occur in different ways, and there are numerous possible combinations between prerequisites, categories, and impacts on the construction environment. Different enterprises, regions and cultures have different prerequisites. Uniformly using average results and implications is not applicable.

Improvisations are present at all the construction site stages, making it difficult to identify and avoid them, requiring strict control of construction processes, investments in cultural change conducive to improvisation and standardization. Only surveying wastes by making-do does not provide enough information for the manager to prevent them from occurring in their next undertaking or task, but it does provide a more robust and interactive analysis of information to minimize them.

With the study it is concluded that instead of the manager concentrating their efforts on correcting all the intercurrences identified in the construction site, they will be able to concentrate resources and management in the stages, teams, and processes which most contribute to greater impacts, or those which are more significant in terms of costs or delays in the works in order to achieve better results. From this particular study, these efforts should be directed towards requalifying the workforce, investments in materials and components which are compatible with the dimensions established in projects, and investments in medium-term planning in order to eliminate interdependent tasks; and lastly, it is still extremely important to analyze the risks linked to the impacts of rework that are directly associated with the decrease in productivity, the waste of material and the lack of terminality and quality reduction.

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WHAT DOES A COMMITMENT TO A PLAN MEAN?

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ABSTRACT

A plan in the making should pull from what creates customer value and from the performers' knowledge and understanding of the context. A plan for commitment should represent the customer's intent in a way that calls for action on the intent's behalf. A promise to commit to a plan happens at many levels and in many forms toward execution, and every promise made becomes a push mechanism to keep that promise. Since a plan represents both push and pull around a commitment, knowledge about these mechanisms can help to understand a plan's function. The main contribution is a reflection on how a plan's push for commitment interacts with emergent situations and an analysis of what part of the commitment is within or outside the scope of the promise and the promiser's influence and control. The promise made committing to a workplan as input to a Percent Plan Complete measurement is used as a practical example. The paper's conclusion arguably strengthens many of the existing parts and principles of the Last Planner System but also gives suggestions for improvement.

KEYWORDS

Complexity, Commitment, Promise, Construction, Project-Based Production.

INTRODUCTION

Any plan or drawing, 3D model, contract, etc. is merely an abstraction and simplification of what it wants to achieve. It is impossible to give a "true" replica of a complex thing or phenomenon. Therefore, any plan simplifies the expected process of making an output. A plan has the function of pushing its intent into action but should also consider how the situation is here and now and how this will affect the plan. Before the execution of a task, a promise to commit to the plan and/or the plan's intent is often made by the performer. A worker on a construction site might say: "I will try to do the task according to the plan", a response from the manager can then be, "No, I want to hear that you say you are going to do the task according to the plan." The divergence in the use of language has a logical connection to the pull and push mechanism at play that is under scrutiny in this paper. The paper is based on reflection initiated by the first author after measuring workflow reliability with Percent Plan Complete and using the 5 Why methodology on tasks that were not done according to the weekly plan. Deviations from the plan happened even though the activities had been marked as sound. In a sound activity, all prerequisites are evaluated as made ready when the task starts. The 5 Whys often pointed

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toward events outside the worker's influence, responsibility, and scope of work. This raised the fundamental question of what the promisers promised when committing to the plan.

THE METHOD AND APPLIED THEORY

The paper presents a conceptual discussion based on a combination of theoretical reasoning and practical and empirical observations in construction projects. This is done through a pragmatic and critical realistic perspective (Ackroyd & Fleetwood, 2005; Sayer, 2004). We use planning approaches such as the Critical Path Method (CPM), the Last Planner System (LPS), Takt planning, Line of Balance, Scrum and Kanban to exemplify and understand the functions of a plan and how different issues can be handled. We apply the principles underpinning the above-mentioned planning approaches in our reasoning about what a plan is, in which the distinction between pull and push plays a significant role. Complexity is conceived as an attribute of planning and production; in this context, we first discuss what a plan and planning is before we address the issue of making promises in planning. To establish the context of complexity the Cynefin framework (Snowden & Boone, 2007) is central, differentiating between complicated and ordered vs. complex and unordered. In addition, we address uncertainty (Hillson, 2016) and unpredictability (emergent factors) in project execution when analyzing the making of promises in a complex setting (Brady & Davies, 2014). Moreover, we use the principal-agent theory when addressing asymmetric information in the relationship between the parties making and using a plan (Martimort & Laffont, 2009). We place the paper as a contribution to Speech Act Theory and Promise-Based Management (Sull and Spinosa 2007; Cleary et al. 2008)

CONTEXT

A construction project consists of several phases, from the front end with project idea and design to the execution phase with production as the main activity. The front end has more positive iterations (Ballard, 2000) and reciprocal interdependencies (Coyote & Thompson, 1967), and has been characterized as the solution of wicked problems (Churchman, 1967; Spitler & Talbot, 2017). It has been suggested to take different metaphysical views in different phases, a process-view in the front end and a thing-view in the execution phase (Ika & Bredillet, 2016). The main context for this paper is production planning. We do however to some degree also look towards design since this in most projects has a close link to the production phase.

COMPLEXITY AS A POINT OF DEPARTURE

We use the definition and differentiation of complexity vs complicated from The Cynefin Framework (Snowden & Boone, 2007). In short, in the complex domain, we cannot forecast cause and effects, and they can only truly be perceived in hindsight. In the complex domain deviations from a plan should be expected to occur, so dynamic and proactive preparations and an agile and flexible way of planning should be used. In the complicated domain, we can identify causes and effects and predictions can be made. If we treat a project as a fundamentally complicated matter, deviations from the plan need not happen. If a deviation still happens, it is an abnormality caused by a fault, lack of planning or underperformance. The Cynefin framework is a sense-making framework, to be used to constantly sense and reflect on the situation you are in. Although a project will contain situations or elements of all domains (simple, complicated, complex and chaotic), we in this paper focus only on the complex (where cause and effect only can be deduced in retrospect) and complicated (where expertise and analysis are needed to find and understand cause and effect.).

THE PRODUCT AND THE PRODUCTION IN CONSTRUCTION

If we use the possibility of prediction as the main distinction between something complex and something only complicated, we position the phenomenon of design as something unpredictable and therefore complex. A design process can result in infinite solutions to the design problem. The final design is often an artifact comprising a complicated network of tasks and interdependencies. When the design has been decided the sequence and way of production can be decided before the actual production starts. A plan can then be made, and if everything is predefined in a logical sequence, the plan is often in its structure on the ordered side of the Cynefin Framework (Snowden & Boone, 2007). The process of putting the artifact together is a social endeavour in a complex context. It also depends on many prerequisites that are not defined to be within the project members' control. The production process then becomes a complex undertaking, but with many elements that are only complicated. The fact that many projects overlap the design process with the production process adds to the complexity of the production process, but we want to stress that this choice does not make the actual product more complex.

THE ACTIVITY

Many plans are made with only a deterministic view of the duration of the activities. This is a simplification of reality with a more stochastic variability since the activity is a process in a complex context. It is difficult to make a promise on ambitious deadline when dealing with an activity with large inherent stochastic variation on its duration, in theory, any promise to be shorter than the worst case cannot be guaranteed. Reduction of internal variability is hence an important task that must be dealt with before a certain duration can be forecasted with accuracy (Spear & Bowen, 1999), but shifting context, a unique product, and a fragmented building sector (Ballard & Howell, 1998) become issues adding complexity. A traditional view of a finished plan before execution can be claimed to be the best way to produce the product. Using Cynefin analogy again, best ways only exist in the clear (simple/obvious) domain (Snowden & Rancati, n.d.). In the complicated domain, you can identify good practices, but they can always be challenged to be better. A point here is that not only the design details but also the production methods used within the activities might be challenged and be under development; this adds to the complexity of reducing variability. If you improve more than one independent variable, the effect of improvement initiatives is hard to single out with small amounts of data. An ambitious promise on duration is difficult to make, even if all prerequisites for the activity are considered sound.

THE PLAN AND THE PLANNING

Using a push/pull analogy, we argue that there are two main functions of a plan; the first is to convey and represent the project's intention to be achieved (pushed from the plan), the second is to learn from the context and adapt accordingly (pulled to the plan). This is described by (Howell, 1999) through the terms planning and control. Howell sees planning as defining criteria for success and producing strategies for achieving objectives, while control is seen as causing events to conform to plan and triggering learning and replanning. Plans are tools made and used by people to plan and control production, that is to both pull and push. Also, a plan made by pull-based planning will when used have a push function. This push is expressed through demand to follow the plan and requests to make reliable promises. The aim of this paper is to zoom in on this push and pull functions, mainly seeing it from the perspective of the people making and using the plan, both pushing and pulling others.

A plan can be seen as an attempt to predict the possible outcome of multiple events. A project is divided into smaller manageable pieces, that is the tasks (activities) we must do to carry out the project. We search for probable causes and effects, recognize patterns, map interdependencies, and try to forecast how the interactions between tasks will play out in the future. However, "*all plans are forecasts, and all forecasts are wrong. Forecast error varies with forecast length and level of detail*"(Ballard & Tommelein, 2021). A plan is normally set up to be ambitious (a stretch goal), a probable outcome or a minimum acceptable outcome. Using principal-agent theory we can see those making the plan as principals and those using it as agents. There will always be some sort of information asymmetry between the principal and the agent. The principal's intentions with the plan might (consciously or unconsciously) not be communicated to the agent. Any plan will be based on presumptions, assumptions, and simplifications that can be interpreted differently by the principal and the agent. How the principal and the agent see and use the plan affects how they relate to and execute the push-and-pull functionality of the plan. As an example, an opportunistic principal might make a plan with stretch goals but communicate it as a probable outcome.

A Takt plan (Dlouhy et al., 2018) pushes a parallelism in the flow of trades or set of activities. The Takt planning method constraints the plan actively by "shaping"(Binninger et al., 2017) the work into equal timeboxes (Birkeland, 2010). Takt can be seen as a cooperative approach with the Last Planner System (Binninger et al., 2017), so Takt can be used within the Last Planner System. A Takt plan pushes towards a demand to stay within timeboxes, and a commitment to the timebox must be done early in the project. The reasoning behind allowing this hard commitment to a timebox, is its ability to align the flow of trades and hence reduce waste and prioritize the production's overall process flow. Critical Path Method also pushes commitment early, but without a demand for parallelism in the trades flow as Takt Planning does. Line of Balance also seeks parallelism but does not push it the same way as takt planning and does it with more involvement and hence also choice of the participants. Parallelism of flowlines is the goal but not always the result from Line of Balance planning, this might be an indication of the power of pushing coherence in Takt planning.

A plan in a construction project is not only an explicit and written plan but also contains elements of tacit knowledge (Nonaka et al., 2000) that project members hold. In the limitations of collecting tacit knowledge also lies the notion that explicit plans are not comprehensive. A plan is a simplification of both the intent of the project but also the context. With simplification, the amount of data needed is reduced, but it also reduces the possibility to grasp the situation.

THE PROCESS OF MAKING READY

The Last Planner System has a systemized approach not to let an initially planned activity be equal to a made-ready activity, it goes through a SHOULD-CAN-WILL process that enables an alignment to the context. An underlying principle of the Last Planner System is both about the quality of assignments and a principle that you only do activities that should and can be done. Pulling the tasks from the context makes the push from the plan much more linked to the maturity and readiness of the task. An assignment of good quality should also be specific and clear in the language of the performer; this means that the assignment must contain what's to be done, where, when, who, and with what. Many projects still have a lot of improvement to make in just following the preparation of the activities. The Last Planner system waits with the final promise for a commitment from the performers until the (weekly) workplan. When a promise is made according to and on elements within the trade's control, the commitment is higher. When the performers finally commit to the workplan, a push also happens here, and this is where we want to reflect on its implication using the Last Planner System as a reference. However, first, we look into some other plan and control systems and methods. Our claim is that none of the planning systems mentioned below has the same level of built-in proactive mechanism towards systematically making tasks ready, though the Takt plan creates an even higher need for this proactive thinking and can therefore have benefits to using the Last Planner Systems logic.

A Takt plans early and high demand for making tasks ready is pushing a proactive attitude and sets a high focus on reducing variability in the tasks; this might force a high need for standardization both on product and process in order to try to push the process of production into the complicated domain. The downside of this can be that value in the product is lost or that the design process is pushed into an even more complex situation to cope with the constraints of standardization.

In the Scrum system, a prioritization and check of readiness is done from the product backlog and into a sprint backlog, but Scrum is positioned for doing this in a shorter timeframe and is for this and other reasons, positioned for an even more complex situation than The Last Planner System. In the Last Planner System, the selection, sequencing, and sizing of activities starts after the phase scheduling, normally at least 6 weeks prior to execution of any task, and continues all the way down to the weekly work plans. The work plan is often at a weekly timespan, but this might differ from the planning context. When put on the work plan the activities should be classified as sound, so the making ready process does in a systematic way stop here, and a promise to commit to the plan is done. Scrum makes a similar commitment to the content and goal of a sprint, and by having sprints in the original length of 2-4 weeks (Sutherland, 2014) this system places a promise on the content entering the sprint.

Some key initiators of agile in the software business created The Agile Manifesto (Fowler & Highsmith, 2001) where one of the principles is “Deliver working software, from a couple of weeks to a couple of months, with a preference to the shorter timescale”. The preference for a shorter time has later been challenged down to a 5-day length of a sprint (Knapp et al., 2016), and even hours depending on the definition. A sprint is a defined time with a defined goal and testable output; there is often an explicit zero tolerance for not meeting these goals within the timebox, when made explicit, this functions as a hard push from the plan to the team in the sprint. The Last Planner System lacks Scrum's defined roles of “The Product Owner” and “The Scrum Master”. The Scrum Master is accountable for the Team's performance, removing impediments, and a facilitator for the team to meet their commitment. The Product Owner is the role of one person that is accountable for backlog management and is the only one with authority to cancel an ongoing sprint if it is found to be obsolete (Schwaber & Sutherland, 2021).

The Agile software community calls a system for “Kanban” which is an alternative to Scrum. The Kanban system is less defined as a common system and has many different versions, more or less based on the principle of Kanban signals or logic related to that (Lage Junior & Godinho Filho, 2010). Kanban systems do not have clearly defined roles and sprints as in Scrum, but there the activities from the backlog are pulled into a Todo board to create a constant flow of activities in the pipeline. The Kanban system is normally more flexible, with longer and shorter pipeline activities pulled from the backlog than Scrum. In defence of Scrum and Kanban, long making-ready processes might hinder the wanted agility of the system.

The Critical Path Method (CPM) is often developed with great detail over a long time span and knowingly or unknowingly then oversimplifies the plan. It is often made static and communicated with a strong signal that this is the “optimal” way of conducting the project. If we go back to the claimed push and pull function of a plan, the strong signal and rigidness of the plan create a strong push to the whole organization.

DISCUSSION

We claim the plan references the project's complicated building blocks, leaving out the complex project creation process. A strong push is sometimes maintained even though it meets a context that, for practical reasons, should be learned and give input for a rescheduling. Practitioners should commit to the plan and the context, but if the gap creates a paradox, the plan might lose commitment, and the risk of total failure of the plan might be the consequence. In many projects, the planning that does not consider the production process can be aligned with driving by looking in the rear-view mirror (Ballard & Tommelein, 2021). If a plan is not aligned with the current state of production, a large amount of the planning capacity might be needed to update the plan. The function of pushing any new signal out to production might be futile. If this happens, the plan has no actual push/pull function toward production, and the functions only work as a benchmark function upward toward project goals. A strong push for an early detailed plan meets challenges when met with emergent situations.

EMERGENCY VS UNCERTANTY

"Only what has already happened may be used for forward-looking decision-making" (Schwaber & Sutherland, 2021).

By only starting tasks that should and can be done, there is an expectation in The Last Planner System that the task is sound before it is put into the (weekly) workplan. But even though a task is qualified as sound, many uncertainties and their potential consequences might have been identified to matter (Hillson & Murray-Webster, 2007). By matter we mean "that, if it occurs, will affect the achievement of objectives" (Hillson, 2016). The identified potential consequences are recommended to become a part of the clarification and negotiation process suggested in the Last Planner System (Ballard & Tommelein, 2021) they can be dealt with beforehand and increase the reliability of conducting the task. But identified uncertainties will for practical reasons only be treated superficially and a promise that is made must have some presumptions and remaining assumptions that the promise cannot have the time to be explicit about. If the uncertainty for getting materials is considered low, there is still some possibility that they will not arrive or be destroyed at the site. There is always a possibility that you for practical reasons leave them out because you consider them low even if they are identified, so even the identified uncertainties can turn into an emergent situation because it happens even with a low probability. The challenge with a complex context is that the unidentified variables can come from a lot of "sleeping" mechanisms and past experience provides only limited assurance for future events. When the event happens, we can go into a retrospect determinism and go into the fallacy of believing that if we only do something to that emerging event nothing more will happen. Since production is often sensed in or close to a complex problem new events will emerge but maybe from a different uncertainty and variables. This might force a promise to be broken or make a re-promise (Macomber et al., 2005).

The Last Planner System follows the principle of learning from breakdowns (Ballard et al., 2009; Ballard & Tommelein, 2021), do we then mean that this is a futile principle since we get emerging events? No, but because we acknowledge emergent situations, we mean that how we learn might differ from believing that the cause is something we can find direct countermeasures to. We need to lift the countermeasures we suggest to be more adaptable and general because we do not know where the next event will emerge, ex. good processes rather than specific tasks. What kind of event is classified as uncertain will be a dynamic definition based on multiple factors.

In this principle lies the measurement of Percent Plan Complete (PPC) which measures the percentage of tasks committed at the start of the week that is being done at the end of the week. This is referred to as a measurement of workflow reliability and activities that have not been done at the end of the week should be analyzed in order to learn from it. The method of "5 Whys" can be used to find the root causes for why it was not conducted as planned and search for "root causes". We claim that in a complex world, a true root cause cannot be found, but the method of using 5Whys often helps the user to go beyond the level of more obvious symptoms and closer to systemic causes. The first writer's experience from testing the "5 whys" is that it quite often is situations outside the trade workers' immediate responsibility that are analyzed as the root cause. So it is in a sense beyond the scope of what they made a promise on earlier. Originally the PPC measure worked on a weekly basis, but the possibility to trace PPC on shorter time intervals has been acknowledged (Ballard & Tommelein, 2021).

A COMMITMENT TO A PLAN

“Projects are a network of commitments” (Ballard & Tommelein, 2021).

A plan contains an element of trust and/or power to be executed. A static plan may need a larger element of power to be effective, especially if the plan deviates from the present and it becomes harder to gain the wanted trust. If the plan is not reached any negative deviations from the plan will often have economic consequences. To avoid this deviation resources are adjusted during the execution of the task to regain any lost time. If the plan is delayed because of something that the trade cannot be blamed for, the demand for compensation for forcing the plan back on time is often presented by the trade in advance. When the trades are involved in the planning the trades not only commit to the plan towards the project management but also to the other trades that are part of the planning process. As an example the Last Planner System facilitates a reversed-phase scheduling process where all trades are often gathered and everyone expresses a common commitment toward each other that they will manage to follow the plan. In our experience, this commitment from one trade to another is an important part when involving the trades in the planning process and the commitment to another trade seems to be just as strong if not even stronger than the commitment to the project management. Our experience is mainly based on a Norwegian culture that has been labelled as a “high trust society” (Covey, 2022) with a flat structure, this might influence the level of commitment among the trades.

A RELIABLE PROMISE TO COMMIT

A promise is a statement of intention made in certain specifiable conditions (Árdal, 1968). Statements may include all kinds of stated confirmation and signs of commitment to follow up a plan, including contracts, handshakes, subtle signals, and spoken utterances. A statement may include both explicit statements like “I promise I will do x” and also “I will do x” due to its implicit obligation in the latter statement (Árdal, 1968). In construction, a contract is a document of a promise between two firms where one firm promises to follow the terms to deliver the contract's content by a negotiated payment. A promise to a plan relates to reliability and how seriously the promise giver takes their promise (Ballard & Tommelein, 2021) and building and rebuilding trust with promises and apologies (Schniter et al., 2013). A promise is, therefore, related to a personal or cultural commitment to the task. An often-important part of people's integrity is to keep their promises. When a promise is not kept and the commitment is not delivered, the blame might be put on the person that promised to deliver, and explanations for not delivering are often noted to be bad excuses and apologies. We want to challenge how a commitment is pushed to give a more nuanced picture of the actual promise.

FROM A PROMISE IS GIVEN TO A PROMISE IS KEPT

One of the five original Last Planner Systems principles is “Make and secure reliable promises” (Ballard et al., 2009), but is a promise something you can do in advance and secure? The principle was in the 2020 benchmark for Last Planner System modified. It has become: “Make and secure reliable promises, and speak up immediately should you lose confidence that you can keep your promises (as opposed to waiting as long as possible and hoping someone else speaks up first).“ (Ballard & Tommelein, 2021). The new version acknowledges that the situation might change after making the promise, but it still signifies that the promise is yours to keep. We want to challenge how a promise is treated in both theory and practice, because of the emergent events that can take several forms. We do this to increase “reliable promising” (Ballard & Tommelein, 2021) by creating a better contract to the promise that a performer can make but also creating a better framework for improvement measures on the tasks that are outside the performer's control. We are not trying to underestimate the importance of respect for each other's concern on the contrary we want to increase the respect by letting the performer and the requestor understand the scope and limitations of the promise and also let the requestor see when the performer goes beyond expectancy to deliver the task that is planned for and reduce the amount of work that no one is accountable for. We use the promise made by the performer as input to a PPC measurement as an example. For simplification, we assume there is perfect communication between the performer and the requestor for the scope of the promise and task that is planned, even though this might be an issue in practical application. The performer makes the promise to do the task after clarification and negotiation according to the Last Planner System (Ballard & Tommelein, 2021) and the task is considered defined, sound, sized and sequenced. The task is put into the workplan and the (weekly) period for the plan starts. Then something emerges that was not accounted for in the initial preparations. We believe that at the moment something emerges having a system that respects what really happens is important to the situation. We currently suggest two questions should be asked about the emerging matter;

- Is the emergent matter within the scope of the promise put into the plan?
- Is the emergent matter within the expertise of the performer/promiser?

If we put those two questions in a matrix (Figure 1) we get 4 quadrants where the emergent matter can be categorized;

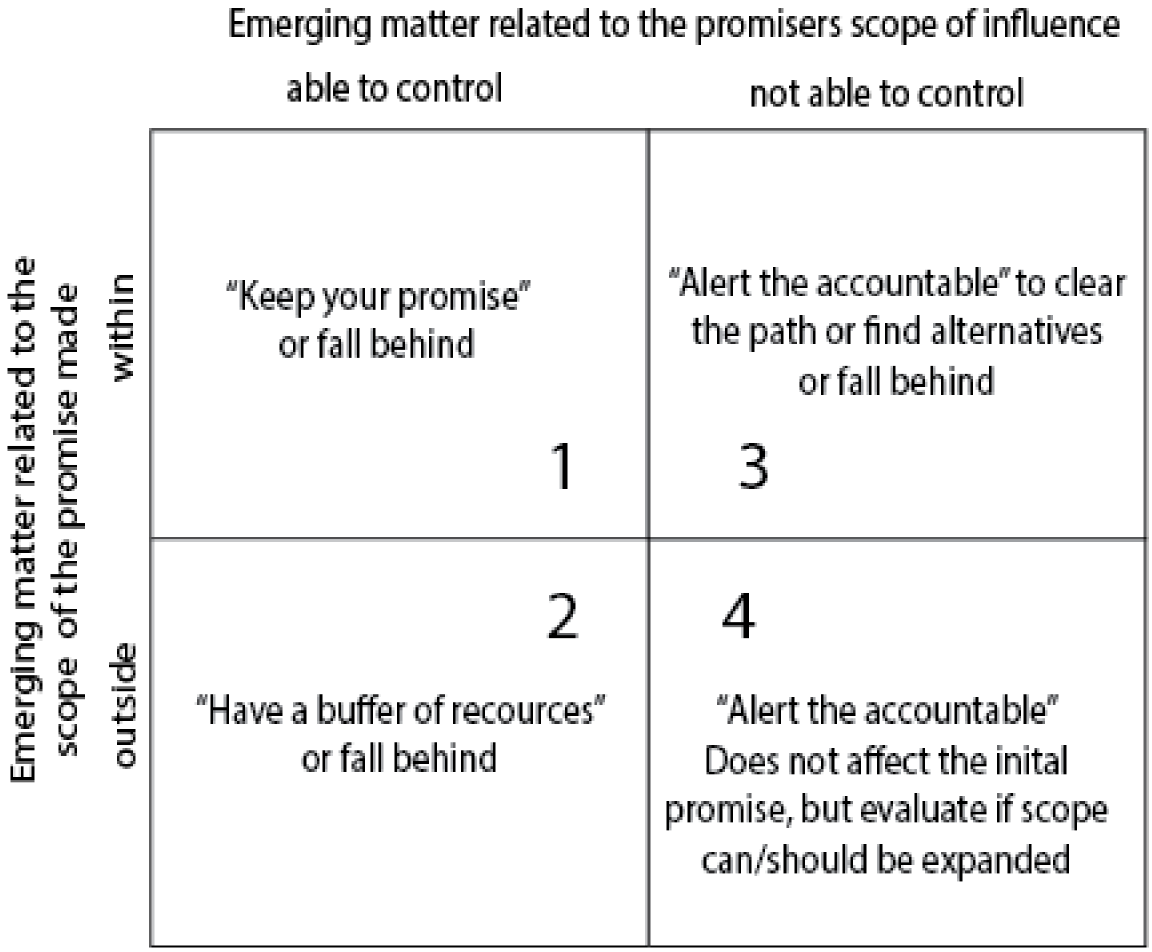

Figure 1: Emerging matter related to scope and expertise.

In quadrants 1 and 2, the performer has expertise within the emergent matter. This means that the performer can have the attitude to deal with those issues, if is not done, it will be because of prioritization or capacity issues. In quadrants 3 and 4 it is outside of the performer, control but in quadrant 3 the matter will still affect the performer's promise, while in quadrant 4 the emergent matter will not be within the promised scope. All the emergent matters can stop the progress of the planned work, but having a language to categorize and communicate and discuss how to deal with them can be useful. It will depend on the consequences of the emergent situation if it becomes a delay or not and the ability to making-do (Koskela, 2004):

- In quadrant 1: The emergent matter will be within both the scope and expertise of the performer. Example: Prerequisites that the performer is accountable in the make-ready process are missing.
- In quadrant 2: The emergent matter will be outside the scope but within the expertise of the performer. Example: An increased amount of work.
- In quadrant 3: The emergent matter will be within the scope but outside the performer's expertise. Example: The previous work is late and occupies the location for the work.
- In quadrant 4: The emergent matter will be both outside the scope and outside the performer's expertise. Example: A change in the content of the work that needs a third party to be solved.

Identifying what quadrant situations emerge might increase motivation for the performer to fix things that are within the control of the performer, but also show the performer's attitude toward fixing obstacles outside influence. It can provide a clearer language to make sure that interfaces between roles are accounted for.

An already identified reduction of PPC measures on work plans down to days and half days will reduce the consequences of emergent matters and will in practice probably need to put the promise part into a daily stand-up meeting setting. This can also give the skilled worker the possibility to promise when the prerequisites are cleared for the whole period, on a weekly plan often not the material, and never the people are prerequisites that can truly be guaranteed.

CONCLUSION

A plan is always a simplification, and when made and committed to a push on behalf of the intent is created. Trades and other project members commit to the plan at different levels and times. When committing and making the promise, they do not account for emerging matters that might affect the plan. Emergent matters are things that you had not anticipated and that will affect the work and the promise to commit to the plan. A higher understanding of the types of consequences the emergent matter can have both on the scope of the promise but also that it can affect outside of the performers space of influence or expertise. The boundaries of the promise and expertise should be recognised to manage the interface between them. Due to the emergent nature of the consequences, it must be a systematic and flexible way of dealing with these interfaces, not case specific. A better understanding of these boundaries might also motivate the performers and get more respect for each other's processes, this can again improve the total workflow reliability.

We suggest that the Last Planner System account for emergent matters when a workplan is made and separates the performer's promise from what cannot be promised by the performer. A shorter timespan on PPC should be considered to give a more reliable promise.

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INTEGRATING A STRATEGIC MILESTONE AND PHASE PLAN (SMPP) AS A NEW LEVEL OF THE LAST PLANNER SYSTEM (LPS): AN INVESTIGATION ON MEGAPROJECTS

Annett Schöttle[1] and Andreas Böker[2]

ABSTRACT

Megaprojects often struggle with their production planning. One of the reasons is a lack of common understanding of the project scope and goals within the project teams and stakeholders as the basis for reliable project delivery. The Last Planner System (LPS) is a well-known method for production planning and control. Nevertheless, the LPS has its limitations in megaprojects as the gap between the master schedule and the phase plan is vast. On the one hand, the master plan consists of the milestones, the phase durations, and overlaps only. On the other hand, the phase plan (also named milestone and phase plan [MPP]) already consists of specified handoffs and conditions between processes within a phase duration. Thus, the master schedule is too vague, and the phase plan is too detailed. To overcome this limitation, the authors propose integrating another level, on a monthly basis, between the master schedule and MPP in the LPS.

Based on two case studies, this paper describes and analyzes how a Strategic Milestone and Phase Plan (SMPP) can be integrated as a new level into the LPS and demonstrates the benefits based on the findings of the two cases. The authors finally conclude that the SMPP should be integrated into the LPS at a new and additional level.

KEYWORDS

Last planner system, strategic milestone and phase plan, megaprojects.

INTRODUCTION

Flyvbjerg (2017) defines megaprojects as "large scale, complex ventures that typically cost $1 billion or more, take many years to develop and build, involve multiple public and private stakeholders, are transformational, and impact millions of people" (p. 2). Challenges often come with this: The development of a huge organization that contains constantly high employer fluctuation, unclear roles and responsibilities, a hierarchical decision-making process, long duration times when it comes to decision-making, lots of stakeholders with different expectations and interests, strong power relations, a lack of clearly defined goals and scope as well as unclear and undefined interfaces, a changing scope over time, technological innovation, a lack of common understanding within the project team, asymmetric information among the different stakeholders, a lack of transparency, a lack of seeing the overall project, working in silos, political interests, political decisions impacting the project (power games), and different financial funding (Flyvbjerg, 2017; Flyvbjerg et al., 2003; Merrow, 1988; Priemus et al., 2013).

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Furthermore, Greiman (2013) points out that "[l]engthy projects create multiple unknowns, ambiguity, uncertainty, and risk that do not exist in projects of much shorter duration" (p. 186). This aligns with the description of Floricel and Miller (2001) that megaprojects contain "anticipated risk and unexpected events" (p. 446). Such risks can be design risks related to the planning phase of the megaproject, construction risks with the project schedule and coordination problems as well as financial and/or economic risks (e.g., Irimia-Diéguez et al., 2014; Little, 2011). With the named challenges, risks, unknown events, and the importance of success to the sponsors, megaprojects can easily fail (Merrow, 1988). Thus, in sum, a megaproject is impacted by a variety of factors that are not clear from the beginning. Hence, the teams must understand the project goals, constraints, risks, and the dynamic of the organizational environment and use a production planning and control method to help them navigate through the project.

In IGLC community, many papers have been published supporting the implementation of the LPS as a production planning and control system. The LPS consists of five steps (1) Master Scheduling, (2) Phase Schedule, (3) Lookahead Planning, (4) Weekly Work Plan, and (5) Learning (Ballard & Tommelein, 2021). Regarding megaprojects and LPS, almost no papers have yet been published (Ibrahim et al., 2017 – hospital project in San Francisco; Leth et al., 2019 – redevelopment of an offshore oil and gas field in the North Sea).

When it comes to a megaproject LPS, we see a gap between the master schedule and the phase plan. On the one hand, the master plan consists of the milestones, the phase durations, and overlaps only. On the other hand, the phase plan already consists of specified handoffs and conditions between processes within a phase duration. Thus, the master schedule is too vague, and the phase plan is too detailed. Therefore, an additional level between both levels is missing when it comes to large or mega projects. Implementing the LPS on two megaprojects allowed the authors to integrate another level into the LPS and research the value of the outcome. Consequently, based on the two cases' findings, we propose to integrate the SMPP as another level into the LPS.

RESEARCH METHOD

The objectives of this research are to introduce the SMPP to the IGLC community and to demonstrate the value of the SMPP as a further level of the LPS based on the two case studies: (1) Stuttgart Main Station Building (Bonatzbau), and (2) Munich Main Station. Therefore, a combination of action research and case study research was used to achieve the research objective as the first author was involved as a consultant/researcher in the second case and the second author was involved as a consultant/researcher in the first case (Dickens & Watkins, 1999; Yin, 2014).

During LPS workshop execution, the authors observed the teams and had small feedback sessions to improve the workshops as well as to define the content/next steps of the following workshops. To better understand the difference between the master schedule and the newly introduced SMPP, worldwide experts were questioned regarding their understanding of the master schedule in January 2023. Furthermore, in January 2023 a survey was carried out to collect data regarding the user experience of the SMPP during the workshops and how the outcome is used. In total, 19 responded to the survey: 42% (response rate 53%, 8 out of 15) from the project team of the first case and 58% from the project team of the second case (response rate 35%, 11 out of 31).

UNDERSTANDING THE MASTER SCHEDULE

To get a better understanding of the master schedule, worldwide experts were asked via mail and call for their definitions of the master schedule (see Table 1). In sum, the master plan can be defined as a general plan based on important milestones and depicts the different phases of the project by considering previous experiences. This is in alignment with the theory where Ballard and Tommelein (2021) defined the master schedule as "set milestones and phase durations and overlaps" (p. 12).

Table 1: Definitions of the master schedule from worldwide experts

Expert	Definition
Ballard, Glenn (USA)	The master schedule consists of the start and end dates of the project phases. The master schedule is produced within a project execution plan that treats risks and opportunities and is examined to see if the risk that remains after developing mitigations is acceptable. Revision may occur in an indefinite number of cycles until a go/no-go decision is made.
Christensen, Randi (DK & UK)	Includes contractual deadlines/milestones and, depending on the duration of the project, 1–4 milestones per year. Besides contractual milestones, potential additional milestones are either fixed based on delivery time (e.g., precast elements, governance processes by official bodies or the like) or some could be set based on a process plan made by the team.
Etges, Bernado (BR)	A plan that splits the project into general work packages (phases) to help define labor and equipment histograms and the flow through the project.
Hackler, Cory (USA)	General outline with milestones and phases based on previous data.
McConaughy, Tammy (USA)	Aligning Project Phases and Key Milestones that also help outline phase pull plans. This includes: (1) Utilizing any milestone information from the owner or other stakeholders, and (2) any baseline schedules that have been created.
Mossmann, Alan (UK)	A Milestone plan is the first level of decomposition of a project. It defines the overall design or construction and logistics strategy; key dates both for the customer and for the delivery team; the conditions of satisfaction for key milestones; the phases of the project for subsequent phase scheduling; and it details the 'last responsible moments' for ordering long-lead items.
Tsao, Cynthia (USA)	Initially, it was meant for milestones for one project, not for multiple projects.

INTEGRATING A NEW LEVEL TO THE LPS

Tsao et al. (2006) suggested that the IGLC community consider broadening the scope of the LPS so that it scales up to assist with portfolio management. Specifically, they recommended that owners start tracking a project-level Planned Precent Complete that measures how well their projects are meeting initial project goals (e.g., budget, schedule, quality, etc.) and start tracking a project-level variances chart that identifies the root causes of not meeting initial project goals (e.g., labor, long-lead item procurement, etc.). With this trending information, the owner could work on improving portfolio management by addressing those root causes when setting up the initial contractual terms and conditions for new projects. While Tsao et al. (2006) focus on portfolio management that would be integrated into the LPS above the level of the master plan, we suggest integrating an SMPP underneath the master schedule regarding the project itself.

Greiman (2013) reported that on The Central Artery/Tunnel Project in Boston, a Milestone Manager Group was successfully installed "to help manage and overcome project delays that resulted from the unpredictable nature of several aspects of the work" (p. 188). Therefore, the project was divided into four major milestones to track the project's progress and develop countermeasures based on the outcome. As this task force focused on the milestones, the SMPP focuses on milestones as well as the phases of the project.

Figure 1 shows the integration of the SMPP as a new level into the LPS and considers the level of portfolio management proposed by Tsao et al. (2006). The SMPP covers the entire project from start to finish including major milestones and their fulfillment criteria, all phases of the project/subprojects, specific handoffs as well as conditions of satisfaction between processes, strategic conditions, and defined premises with possible alternatives.

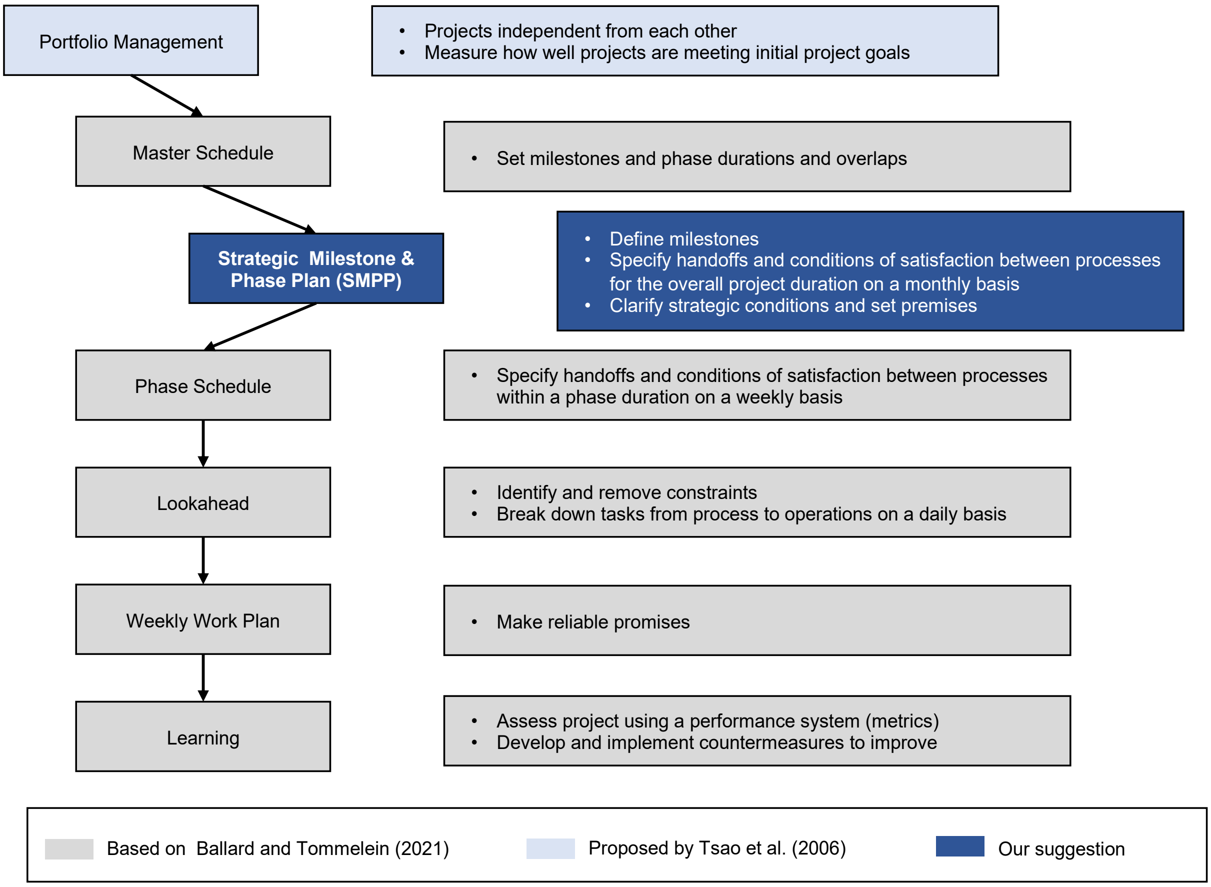

Figure 1: Integration of the SMPP into the LPS

CASE STUDIES

The case studies presented are both main stations in the south of Germany (Stuttgart and Munich) that are part of the infrastructure expansion from the German national railroad company (Deutsche Bahn, DB). Thus, both are capital projects in which the owner initiated the implementation of the LPS. In both projects, the SMPP was integrated as part of the LPS.

CASE 1: STUTTGART MAIN STATION BUILDING (BONATZBAU)

As part of the infrastructure project, Stuttgart 21 (reorganization of the railroad hub), the historic main station building (Bonatzbau) will be completely modernized. The renovated building, in addition to a new stabilizing structure, will contain two floors of a shopping mall as well as a hotel including a lounge and meeting areas. The exterior walls of the almost 100-year-old building are under preservation. The future main entrance allows easy access to the tracks of the new platform hall, which too, is currently under construction. Overall, the investment cost of the whole Stuttgart 21 project is currently indicated at €9.8 billion, of which €200 million is attributed to the historic main station building.

When the new project manager took over in 2020, he found that the team didn't have a common understanding of the project's goals and scope. Searching for an approach that would help the team achieve the milestones brought up the idea of implementing the LPS. Thus, a workshop series was rolled out to implement the LPS. By that time the project was in the phase of demolition and schematic design. After a project status check, a lean competence workshop, and an Overall Process Analysis (OPA) the SMPP was set up in two workshops for a period of five years (see Figure 2). Based on the SMPP, a weekly MPP was defined in May 2021 to set up a complete LPS for demolition and renovation works. In parallel, the basic design for the new building was further developed which led to an adaptation of the SMPP in four additional sessions from December 2021 to February 2022. To assure a flow from the demolition and renovation works to ground works as well as core and shell works, the schematic and detailed design development was included in the LPS.

Figure 2: SMPP Bonatzbau, 2021

CASE 2: MUNICH MAIN STATION

The core system of the city train (1.SBSS) needs a second core line (2.SBSS) as the first is overloaded. Accordingly, the main station needs to be extended and modernized—this includes overground and underground work. Besides the existing operations, all other buildings will be demolished, and new buildings will be built including services areas, areas for restaurants, shops, and office spaces. The project also incorporates a precautionary tunnel for another subway line as well as the complete renovation of the track hall roof and a new cross-platform roof. Thus, they are building under and overground while the fast trains, city trains, and underground lines are still operating, and services need to be provided for the customers. The anticipated cost for the main station (overground) is estimated at €1.2 billion and the expected cost for the 2.SBSS is approximately €7.2 billion.

In mid-2021 the development of the project organization started with the assignment of a project lead. The project lead was involved in the project team from the first case study. Drawing on his experience of the effect of the workshop series from the first case and understanding of how important it is to tear down silos and enhance communication between participants across different areas of responsibility, a workshop series was rolled out while the project was in different design stages. The project lead intended to reorganize the project organization based on the outcome of the SMPP:

"We intended to develop an SMPP based on lean principles [pull from the last process step of the commissioning process] to achieve a shared and deep understanding of the project program and scope as well as the necessary structure of the subprojects to define the overall project structure and develop a project organization that aligns with the project [...] and we did. Based on the SMPP outcome we structured, developed, and formed our project organization from scratch. [...] Because our organizational structure reflects this new project structure it is part of the project DNA and therefore will continue to grow naturally. This also ensures that lean and the strategic direction of the project no longer have to be carried into the project [...] [and they] will remain as part of the project from the inside out." (André Haubrich, DB Netz AG, April 2023)

In total, seven full days of SMPP workshops were necessary to produce an overall picture—the first four workshops were executed in April and May 2022, and the last three workshops were executed in September and October. The break between the workshops became necessary for the team to work off defined actions and to reflect on and adjust the defined premises outlined in the SMPP. It needs to be said that the workshops consist of a core owner team of 10–12 people and additional people that were brought in to work on specific topics. The SMPP was developed for a period of 15 years, aiming for completion at the end of 2035. Figure 3 shows an extract of eight years of the SMPP and Figure 4 the digitalization of the whole SMPP. In between the SMPP workshops, in June 2022, a strategic meeting with the project managers regarding the roles and responsibilities occurred. In addition, in May and June, four workshops were held to analyze the personnel requirements, not only for the main station but also for the whole project. The journey then continued with further workshops regarding the reorganization. Additionally, the team decided to continue learning by developing the MPP on a weekly basis to achieve the first major milestone of the project in January 2026 (duration of MPP 34 months).

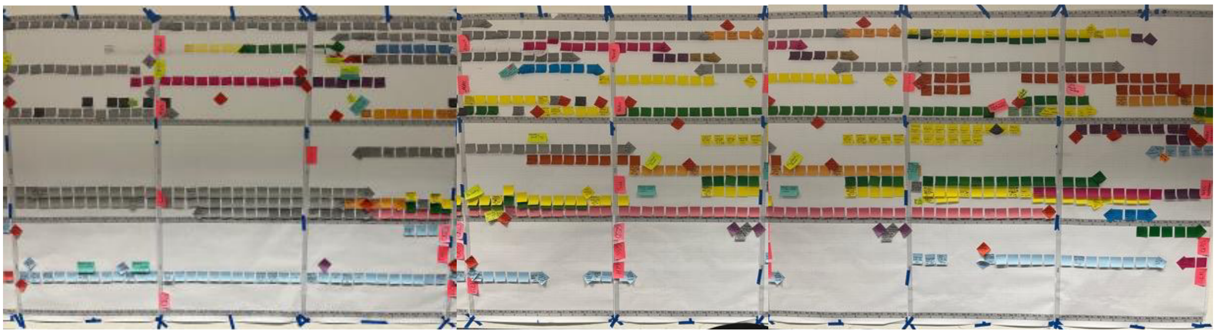

Figure 3: Extract of SMPP Munich Main Station, 2022

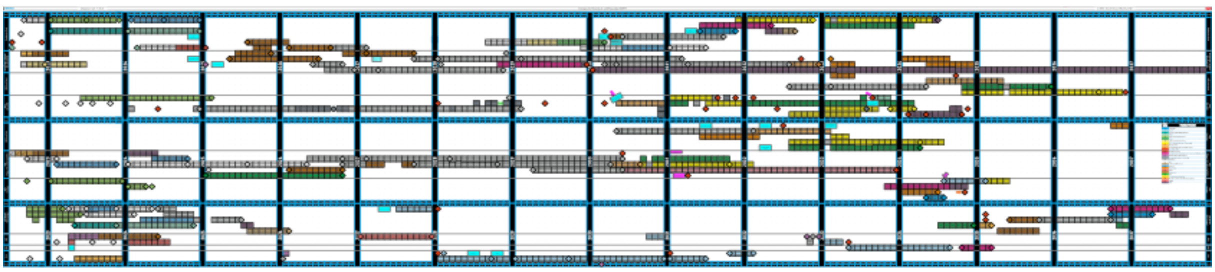

Figure 4: Digitalisation of the SMPP Munich Main Station, 2022

IMPLEMENTATION OVERVIEW

In the Stuttgart main station building project the SMPP was used as the basis to set up a complete LPS followed by an MPP, a six-week lookahead, and weekly work plans to steer and control the overall project delivery. In addition, it was transferred into the overall schedule of the project of the whole reorganization of the railroad junction. In the Munich project, the SMPP was used to better understand the project to restructure its organization. Afterward, the SMPP was transferred into an MS project timetable which is currently supposed to be the control schedule. In March 2023, the team started with workshops to develop an MPP.

Table 2: Overview of the workshop series and execution time for both cases

Workshops	Description	Bonatzbau	Munich Main Station
Project status check	Common collection and assessment of risks, obstacles, opportunities, and drivers of the project.	One workshop, March 2021.	One workshop, February 2022.
LPS competence workshop	Villego simulation to learn about the LPS.	One workshop, March 2021.	Two workshops, February and March 2022.
Condition of Satisfaction	Development of a common goal understanding for the project with a definition of what "success" means for the project team.	Not part of the tendering.	One workshop, February 2022.
Definition of the milestones	Definition of the important project milestones and specification of the compilation criteria of the most important milestones (20% of the project milestones).	Included in the OPA.	One workshop, February 2022.
OPA	Time-independent process analysis to determine and record the project-relevant interfaces.	Two workshops, April 2021.	Three workshops, March 2021.
SMPP	Pull planning from the last project milestone on a monthly basis for the whole project timeline.	Two workshops, April 2021.	Seven workshops: First four workshops, April and May 2022. Last three workshops, September and October 2022.

DISCUSSION OF CROSS CASE FINDINGS

FINDINGS COMPARING IMPLEMENTATION

In both projects, the SMPP was implemented successfully following the different requirements of the project leads. When comparing the implementation of both projects, there are six differences:

1. **Duration of SMPP:** In Case 1 the schedule duration is five years, while in Case 2 the SMPP covers a period of 15 years.
2. **SMPP scope:** Case 1 is a large project that is an integral part of a megaproject, while Case 2 is a megaproject including subprojects.

3. **Project phase when SMPP was developed:** In Case 1 the project was already under deconstruction and in the design phase of construction documents, while in Case 2 the project was mainly in the design development stage.
4. **Intention of the owner regarding SMPP:** In Case 1 the owner's intention was to get a project overview including the main dependencies between design, deconstruction, construction, and the different building parts. While in Case 2, the intention was to restructure the project organization based on the project's needs.
5. **Action of the owner:** In Case 1 the project was already in progress when the implementation started (reactively), while in Case 2 the implementation was used to set up the project (proactively).
6. **Availability of project participants:** In Case 1 the contractors for demolition and structural works were partly involved in developing the SMPP, while in Case 2 just the owner's team participated in the workshops as the tendering process did not start yet.

The differences show that the SMPP is flexible in its application and focus. Thus, there are no constraints on the time the SMPP should be developed; however, the criteria can be set that the earlier the SMPP is developed, the better.

SURVEY FINDINGS

Before being asked about their SMPP experience, participants were first asked about their pain points regarding the traditional scheduling process of megaprojects to obtain a reference point. Overall, the answers can be clustered into seven major points: (1) political deadlines; (2) missing identification and a lack of understanding of interfaces, dependencies, risks, and responsibilities; (3) lack of communication and information regarding goals and tasks; (4) missing integration of relevant stakeholders and their knowledge; (5) missing focus of the overall project; (6) lack of common understanding among the project team; (7) lack of moderation during development. The pain points result in an unreliable schedule that contains unrealistic durations and impossible sequences.

Participants were then asked how helpful the SMPP workshops were and how helpful the outcome was for furthering the procedure of the project. For most of the participants, 79%, the workshops, as well as the outcome, were extremely or very helpful. Furthermore, 11% answered that the SMPP workshops were somewhat helpful (see Figure 5). Only one person (5%) answered that the SMPP was not helpful, and one person (5%) checked the box of no answers. Overall, it can be stated that the SMPP was very helpful for both project teams. In further questions, the survey participants were asked to give more insights based on open-ended questions. Participants mentioned that simplification and visualization helped to get a better overall view of the relevant processes and dependencies without getting lost in detail. In addition, the information and knowledge exchange and solution-finding collaborations supported by neutral moderation helped to gain a common understanding of the project and critical aspects. It also helped to identify missing dependencies, gaps, prerequisites, and related challenges. They finally stated that the SMPP should be set up as early as possible.

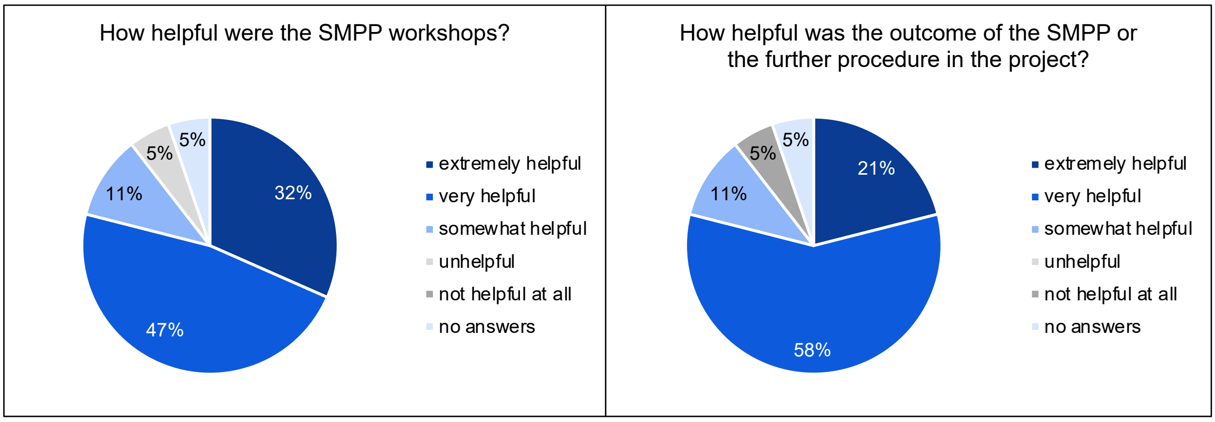

Figure 5: Response of the survey participants regarding the SMPP workshops and outcome

Overall, the survey participants highlighted the following advantages of the SMPP:

- Overview of the entire project on an intermediate and manageable level (measurable).
- Increased focus on relevant steps and long-term scope sequencing/milestones.
- Plausibility check of the total construction time and handoffs.
- Simplification of complicated issues using a common (simple) language.
- Creation of a common understanding of the goals and subsequent steps.
- Exchange of valuable information.
- Involvement of all project participants.
- Joint development process.
- Increased focus on relevant steps and results through pull-planning.
- Transparent and structured presentation of the project.
- It allows the development of a different perspective.
- The holistic approach.
- A better understanding of the current project status.

With the last question of the survey, participants were asked how often the SMPP should be updated (see figure 6). Most participants stated that a smaller time duration (every three or six months) would be better because of the dynamic and resulting changes. A smaller period would also help new project members get a better understanding and check on the intermediate milestones to maintain awareness regarding the overall project milestones.

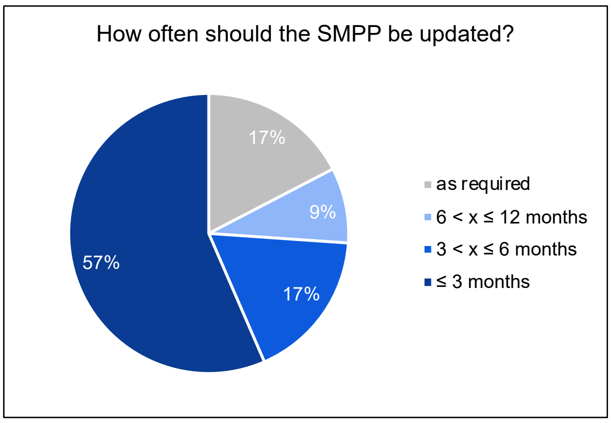

Figure 6: Response on the sequence of updating the SMPP through workshops

CONCLUSION AND RECOMMENDATION

The case studies presented in this paper show the research and findings of the implementation of the SMPP into the LPS of two megaprojects. In the presented cases, the SMPP was developed for a mid (five years in Case 1) and long time period (15 years in Case 2). In both cases, the implementation of the SMPP was a significant benefit for the project teams. It helped to achieve a common understanding of the overall project schedule, related interfaces, and process dependencies. It also helped to close the gap between the master schedule and the MPP. Thus, our recommendation is to implement the SMPP as early as possible in a project. Furthermore, we recommend adding the SMPP to every LPS implementation for projects if it is necessary to generate a full project overview with the project team, the time frame is a minimum of 18 months, and the project is highly complex. If otherwise, the phase plan could be extended.

As both cases are still ongoing projects, the value of the SMPP cannot be evaluated with finality. Also, as in both cases the SMPP was developed for five and 15 years, the value of adding this level to a smaller project with a three-year duration might be beneficial, but this cannot be verified yet. Furthermore, what would happen if the project duration and thus, the SMPP, were more than 15 years? We assume that the SMPP would then be revised at different, wider intervals for the entire period. For example, instead of monthly, it would be quarterly, with the first years being on a weekly basis. The switch from monthly to quarterly depends on the project stage, the available information, and the independence of the project - the shift from weeks to quarters might be between five to eight years.

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LEAN CONSTRUCTION AND AWP: SIMILARITIES, DIFFERENCES, AND OPPORTUNITIES

Slim Rebai[1], Wassim AlBalkhy[2], Olfa Hamdi[3], and Zoubeir Lafhaj[4]

ABSTRACT

The registered levels of failure in construction projects encouraged searching for new concepts and methods to improve the performance of these projects. Lean construction and Advanced Work Packaging (AWP) are examples of these concepts. While lean construction has been practiced for three decades, AWP is still newer. Despite the growing interest in Advanced Work Packaging (AWP) and Lean Construction, there is currently no published research that explores the feasibility and effectiveness of applying AWP and Lean Construction in construction projects. The current study aims to provide a comparison between the two concepts based on the results from reviewing the literature. This study, which covered 29 studies, summarizes similarities and differences between lean and AWP based on four categories; context and principles, project specification, roles in the project, and work approach. Based on the results, the study recommends investing in ways to integrate the two concepts aiming at achieving better performance on all levels and decreasing the impact of uncertainty and complexity in construction projects.

KEYWORDS

Lean construction, Advanced Work Packaging (AWP), construction projects, Last Planner System (LPS), comparison, literature review.

INTRODUCTION

During the last few decades, the increased levels of complexity and rates of failure to deliver construction projects on time, with the planned cost, and with good quality have encouraged the movement toward the adoption of new concepts that are more related to thinking about construction as a production system (Farghaly & Soman, 2021). Unlike the traditional project management theory, understanding construction as a production system means that construction systems should be designed, controlled, and improved based on three goals improving the intended produced product, improving the production process and its characteristics (e.g. cost minimization), and meeting the needs and requirements of the customer (e.g. quality) (Koskela et al., 2002; Koskela & Howell, 2002).

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Lean Construction and its related applications and tools such as the Last Planner System (LPS) and Integrated Project Delivery (IPD) and more recently, Advanced Work Packaging (AWP) are examples of the concepts to support the management and control of construction production systems (Farghaly & Soman, 2021). In many locations around the world, the implementation of lean construction has shown improvements on various levels including cost saving, project duration reduction, higher safety awareness and fewer accidents rates, sustainability, errors and rework reduction, wastes reduction, better inventory management, higher predictability of work, higher labor productivity and increasing customer satisfaction (Albalkhy & Sweis, 2021). The concept of AWP is still new compared to lean construction but shows positive signs about its ability to improve performance in construction projects. For instance, a study that included 20 construction projects in the United States and Canada showed that implementing AWP helped achieve better predictability and improved productivity, cost, safety, and quality (Hamdi & Lafhaj, 2021; O'Brien et al., 2016). Some estimates showed that AWP can help achieve around 25% gain in productivity and 10% installation cost savings in construction projects (CII & COAA, 2013; Rebai et al., 2022). Accordingly, research and interest in AWP are increasing.

Although Advanced Work Packaging (AWP) and Lean Construction have been shown to have significant benefits in enhancing construction productivity and efficiency, their feasibility and efficacy have yet to be examined in the scientific community via a research article. Although both concepts aim to improve performance and productivity in construction projects, the link between them to provide more chances for project success remains inadequately explored. An essential question to be asked is how the two concepts can complement each other. The present study investigates the similarities and differences between AWP and Lean Construction by reviewing the existing literature to address this inquiry.

DEFINITIONS

Lean Construction

Lean originated following the development of the Toyota Production System (TPS) in Japan. Since then, there have been many works that aimed to describe TPS and the principles and theory of lean (Liker, 2004; Ohno, 1988; Womack et al., 1990; Womack & Jones, 1996). In these works, lean principles were defined based on the identification of value based on the client's needs and requirements, value stream mapping, creating a flow of information and materials and waste elimination, establishing pull and producing only what is needed, achieving continuous improvement, and respect for partners and people.

The success of lean in Toyota encouraged its implementation in other fields; including the construction field. The first work about lean construction was the presentation of the "new production philosophy to construction" by Lauri Koskela (1992), which was then followed by the Transformation-Flow-Value theory (TFV) in 2000 (Koskela, 2000). Another important work was the presentation of the most famous lean tool, the Last Planner System (LPS) (Ballard, 2000). LPS can be understood as a planning and production control tool that integrates collaborative planning with all possible stakeholders especially the last planner (people who do the work), incorporates the pull concept and plan based on what "CAN" be done instead of the push mechanism that is based only on what "SHOULD" be done, identifies constraints to be removed, develops performance measures such as Planned-Percent-Completed (PPC), and integrates learning process based on the principles of continuous improvement and non-compliance to plan analysis (Porwal et al., 2010).

LPS and TFV together helped to construct a base for the theoretical and practical streams of the theory of lean in the construction sector (Albalkhy & Sweis, 2021). Over the years, there has been no agreement on a specific definition for lean construction, but one of the definitions that were raised following studying a list of existing literature about lean construction was *"a philosophy that aims to improve the collaboration between all project stakeholders to maximize value for all of them in general and the customer in particular, in addition to eliminating all kind of wastes, achieving continuous improvement, improving flow, reducing cost and enhancing safety and quality"* (Albalkhy & Sweis, 2021).

AWP

AWP roots go back to the development of Workface Planning (WFP), which was one of the best practices to face the challenges facing the construction of oil and gas projects in Alberta according to the Construction Owners Association of Alberta (COAA) (Hamdi, 2013). WFP is "*the process of organizing and delivering all the elements necessary, before the work is started, to enable craft persons to perform quality work in a safe, effective, and efficient manner. This is accomplished by breaking down (planning) construction work by trade into discrete work packages that completely describe/cover the scope of work for a given project to efficiently use available resources and track progress"* (Hamdi, 2013). In 2011, a joint research work between COAA and the Construction Industry Institute (CII) started aiming at reviewing different methods (including WFP and LPS) and developing a project planning and execution model. The research was based on studying industry cases, literature review, interviews with experts, and team experience resulted in the development of the AWP approach (Halala & Fayek, 2019). According to the CII (CII - RR272-11, 2013), AWP is *"a planned, executable process that encompasses the work on an engineering, procurement, and construction, beginning with initial planning and continuing through detailed design and construction execution"*.

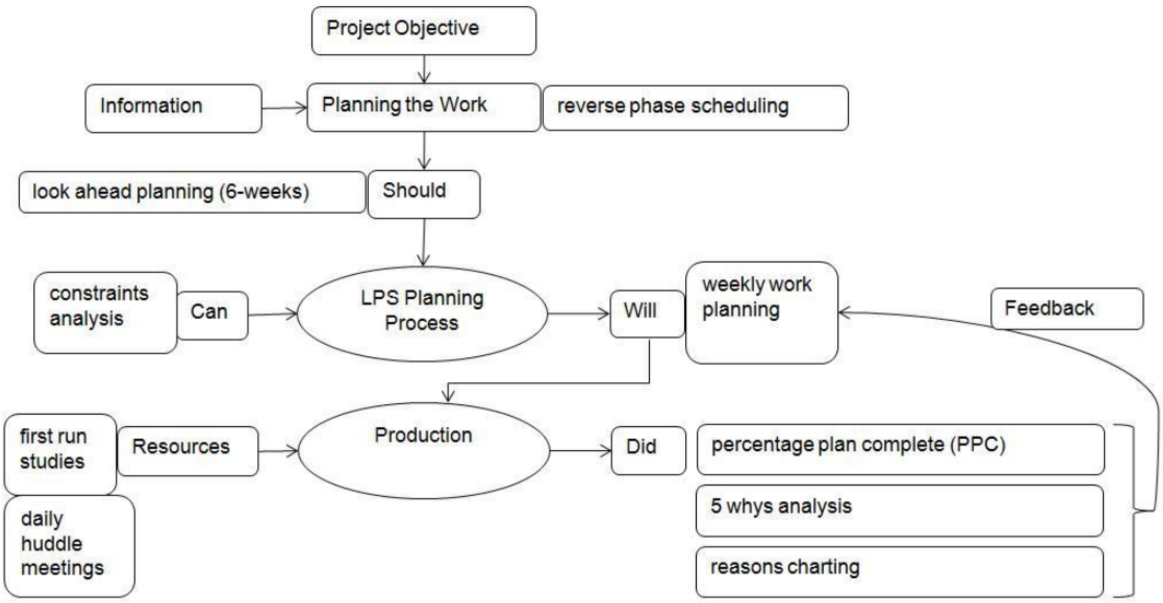

Figure 1: LPS planning process (Porwal et al., 2010).

AWP is a construction-driven project delivery process that begins with the end in mind, in which construction and engineering must collaborate during planning to create a constraint-free field environment (Wu et al., 2021). This collaboration ensures that the project is designed with a construction-friendly sequence and that the supply chain is sequenced accordingly by breaking down the project scope into Construction and Engineering Work Packages (Ponticelli et al., 2015). AWP was also designed to facilitate the planning process and reduce the burden while creating work packaging by removing any possible constraints as early as possible (Halala, 2018). Unlike traditional work packaging where planning is done only in the early phases of the project, AWP tries to provide a holistic approach to planning and execution of work packaging along the whole project life cycle as follows (Olfa et al., 2013; Ponticelli et al., 2015):

- The first stage of a project involves identifying critical planning elements to define work packaging deliverables. The project is divided into Construction Work Packages (CWPs) which align with the execution plan and Engineering Work Packages (EWPs).
- The second stage is Detailed Engineering which refines the work from the first stage. Output includes detailed specifications for EWPs, a discipline-based schedule, and aligning plans to ensure consistency.
- The third stage is Construction, with detailed planning and execution of Installation Work Packages (IWPs). IWPs are issued 3 weeks before the start and are approved by frontline personnel. After execution, IWPs are controlled by owner representatives for quality checks and updates.

Despite receiving some criticism from the Lean community due to the expected impact on inventory growth, push orientation, and variability increase (Arbulu & Shenoy, 2021; Tommelein & Ballard, 2016), there have been several calls to integrate AWP and lean construction, especially by the CII and the Lean Construction Institute (LCI) (CII & LCI, 2022a, 2022b; CIIBuilds, 2022b, 2022a). Nevertheless, a scientific paper still has not addressed the possibility of applying AWP and LCI.

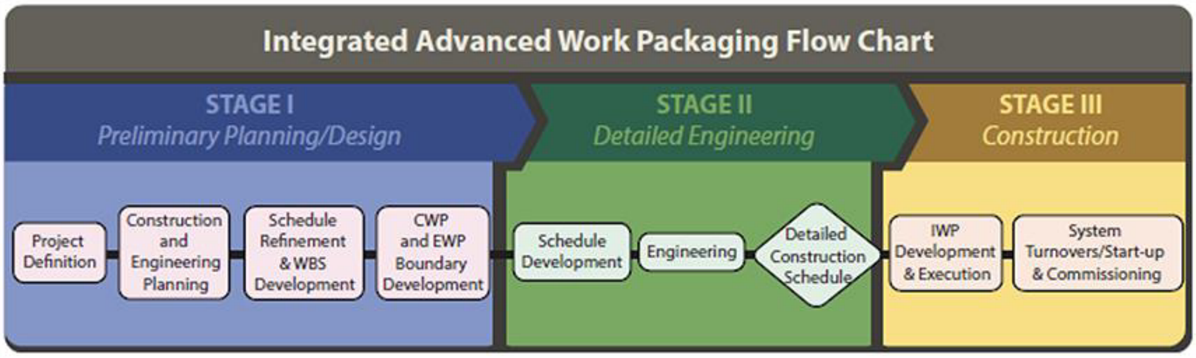

Figure 2: AWP flowchart (CII - RR272-11, 2013).

RESEARCH METHODOLOGY

This study aims to conduct a comparison between lean construction and AWP to identify similarities, differences, and possible opportunities. To do so, a literature review was conducted using a search for the keywords: ((“advanced work packaging” OR AWP) OR (“workface planning” OR WFP)) AND (construction or building). The focus on AWP is because of the low number of publications about it in comparison to lean. The search was done firstly on Google Scholar, Web of Science, and Scopus to cover the scientific articles about the studied topic. Then, it includes other resources; especially those published by CII.

The total number of studies included in the literature was 29. The charactersitcs of the studies are shown in Table 1. Following the analysis of these studies, four main categories were studied, which are context and culture, project specification, roles in the project, and work approach. The selection of these four main categories in this study was based on their relevance to the implementation of Advanced Work Packaging (AWP) and Lean Construction in construction projects. These categories were chosen to explore the factors that could affect the implementation and success of AWP and Lean Construction in various project contexts and organizational cultures.

Table 1: Literature characteristics.

Characteristics		Number of publications
Type of publication	Journal Article	11
	Conference	4
	Book	2
	Thesis	3
	Report	7
	White paper	2
Year of Publication	2013	3
	2014	-
	2015	2
	2016	2
	2017	1
	2018	2
	2019	2
	2020	6
	2021	4
	2022	8
	2023	1

The category of context and culture was included due to its broader organizational and cultural factors that can impact the implementation of AWP and Lean Construction. Project specification was identified as a category due to its critical role in determining the scope and objectives of the project, which could influence the selection of the appropriate work approach, roles, and responsibilities required for AWP and Lean Construction implementation. Roles in the project were selected as a category due to the need for clearly defined roles and responsibilities for the successful implementation of AWP and Lean Construction. Finally, the work approach was chosen as a category to analyze the implementation of AWP and Lean Construction in the context of the project management approach used, as well as the availability of technology and resources necessary for successful implementation. Due to the presence of different lean tools, the fourth part, which is about the work approach provides a comparison between AWP and LPS as LPS is the most known planning and control tool in lean thinking.

RESULTS

Context and principles

Context includes the type of each concept, origin, orientation, and purpose as explained in the literature. The comparison based on the context is shown in Table 2. Concerning the type, it is agreed that lean is not based on a specific tool or methodology; rather, it resulted from a set of principles that were first coined in the automotive industry and constitute what is called lean thinking. Accordingly, lean can be seen as a philosophy based on which different tools and methodologies were developed (Albalkhy & Sweis, 2021; CII & LCI, 2022a). On another hand, AWP is an approach or a methodology that was considered a best practice in work packaging to solve the problems facing construction in the oil and gas sector as explained by the (CII - RR272-11, 2013). In terms of orientation and purpose, AWP can be considered a task-oriented approach that aims to improve task management to increase predictability and productivity in projects (Halala, 2018). While lean has evolved to be more of a human-centric approach that values workers' engagement and is based on collaboration to create value, flow, and continuous improvement (Santos et al., 2021). Orientation toward "respect for people" and collaboration made it possible for lean to go beyond time, cost, and quality improvement to cover other aspects such as innovation and integration of workers' ideas, sustainability, and safety (CII & LCI, 2022a). This does not mean that AWP neglects the human factor. For instance, Path of Construction (POC), which is an essential practice in AWP should be jointly developed and aligned with respect to all stakeholders (CII & LCI, 2022b). Additionally, according to CII and LCI, a key value for AWP and lean construction is integrating the safety, health, and well-being of workers in the process design (CII & LCI, 2022a).

Table 2: AWP vs Lean- context

Context		
Criteria	**AWP**	**Lean Construction**
Type	Methodology	Philosophy
Origin	Oil & Gas Industry	Automotive Industry
Orientation	Task-oriented	People-oriented
Main Purpose	Increase productivity, predictability, and efficiency	Value creation, flow, and continuous improvement

Project Specification

AWP method was developed to respond to the increased complexity of capital construction projects (Halala, 2018). According to Hamdi (Hamdi, 2022), the implementation of AWP in small projects is possible but not attractive as it fits more megaprojects. In contrast, lean can be implemented in all types of projects (Albalkhy & Sweis, 2022). Concerning the contractual relationships and project delivery types, AWP considers early contracting a priority, in which the requirements for AWP and AWP language (plans, procedures, strategies, and responsibilities) should be clearly stated and included in the contract (Halala & Fayek, 2019). For lean, lean can be used with different types of contracting and project delivery methods. However, the lean community has had a big role in the development and adoption of collaborative delivery methods such as lean project delivery system (LPDS), integrated project delivery (IPD), target value delivery (TVD), and others (CII & LCI, 2022a; Koskela et al., 2002). Referring to the costing strategy, the AWP requires defining the initial conceptual model and estimate based on the work packages and then conducting formal cost-saving ideas, which results in the locking of the estimate (CIIBuilds, 2022b). For lean, one of the most encouraged practices is the Target Value Design (TVD), which is based on keeping the design and costs aligned with the client's target cost defined in the early design phase (Ng & Hall, 2019). Regarding the project planning methods, AWP conducts interactive planning sessions, which include all key stakeholders and are driven by the construction, until the preparation of the CWP (Construction work packages) with a push aspect in the CWP release matrix, but once on the site, the workforce planner changed the concept dealing with the IWP (Installation work packages) release plan in a pull concept. The pull could also be promoted when a supplier needs to provide relevant information to Procurement Work Package(CII, 2020). All that is always conforming to the main plan and with the alignment to the POC (path of construction) and (CIIBuilds, 2022b). On another hand, lean construction strictly focuses on pull planning and builds its plans using a collaborative planning method in presence of all stakeholders and participants (CII & LCI, 2022a). The comparison based on project specification is shown in Table 3.

Table 3: AWP vs Lean- Project specifications.

Project Specifications		
Criteria	**AWP**	**Lean Construction**
Suitability	Capital Projects	All types of Projects
Contracting and project delivery	Contracting strategy is a priority and needs to be defined	Different types of delivery but encouraging IPD
Costing/value	Initial conceptual model and estimate Conducting formal cost-saving ideas	Target value design (TVD)
Planning Principle	Push and interactive planning Pull for supplier and PWP, and in the site	Pull and collaborative planning

Roles in the project

As AWP is a structured approach, it has clear definitions for various roles, which is not the case in lean. For instance, while in lean, clients are the main focus and their presence and participation is a key to success in all project phases (Albalkhy & Sweis, 2021), there is no strict definition of their representatives like that in AWP. AWP champions, who act as the voice of the client are responsible for the implementation of AWP procedures and standards throughout the project (Hamdi, 2022). Additionally, while the collaborative planning sessions require the attendance of all possible stakeholders in LPS, there is no strict requirement to make someone a facilitator. In contrast, AWP interactive sessions are usually led by the Construction Manager (1^{st} to 3^{rd} levels of planning) and then workface planners (4^{th} and 5^{th} levels of planning) (Hamdi, 2022). The workface planners are responsible for IWPs definition and management on site to ensure the removal of constraints and the proper execution of the work (CII & LCI, 2022a). A clear definition of lean roles can be found in the last planner which refers to the foreman or the frontline supervisor who has to engage in constraints management and removal (Porwal et al., 2010).

Work approach

AWP is a structured approach that has three main phases of work that are resulting in the CWPs, EWPs, and IWPs. The work in AWP usually starts with area-based decomposition by developing the construction work areas (CWAs) and then over the disciplines-based planning and control. As an approach with origins from the oil and gas sector, during the planning process, AWP focuses on aspects such as constructability, operability, maintainability, and constraint removal (CIIBuilds, 2022b). In turn, lean practices in LPS adopt the short-range production planning levels (i.e. master schedule, phase or pull planning, look-ahead planning, weekly work planning, and daily huddle meetings and learning). Aligned with some practices such as takt planning, short-range planning in LPS aims to ensure the avoidance of overlapping between trades and remove variability sources that may hinder the flow of the work (CII & LCI, 2022a).

Concerning performance measurement, AWP relies on productivity measures for the CWP, and EWP, in addition to safety and delay indicators. It also uses the installation cost of IWPs and their conformity with the planned budget (Halala & Fayek, 2019; Hamdi, 2013; Rebai et al., 2022). In lean, as stated earlier, the focus is on trying to achieve continuous improvement in all possible aspects (e.g. client satisfaction, safety, sustainability, time, cost, and quality). Specifically, in LPS, different measures are considered to cover different aspects including for instance the percent plan complete (PPC), which helps to identify the deviation between what was planned and what was executed (Ballard, 2000). In addition to other measures such as cost reporting (CR), schedule variation (SV), quality reporting (QA/QC), Root-cause Analysis (RA), and Reason Summary for non-competition (RS) (España et al., 2012).

Regarding the learning process, AWP refers to knowledge management related to the IWP process and value chain (Hamdi, 2022). In lean, the learning process is a fundamental concept that supports the continuous improvement goal. Therefore, many tools can be used to support the learning process in LPS such as the analysis of the frequency of plan failures, 5 Whys, Plan–Do–Check–Act (PDCA), Detect–Correct–Analyze–Prevent, variance analysis and the reason for variance (Hannis Ansah et al., 2016). Table 4 summarizes the comparison between AWP and LPS in relation to the work approach.

Table 4: AWP vs Lean- Work approach.

Work approach		
Criteria	**AWP**	**Lean Construction (LPS)**
Planning Structure	Milestone Planning L1 Planning (Areas) L2 Planning (Disciplines) L3 Planning (Work for a crew) CWA, CWP, EWP, IWP	Master Schedule Phase Scheduling Look-Ahead Planning Weekly Planning Daily huddle meetings and learning
Risk	Systemized risk analysis and constraints removal	Constraints removal throughout the whole project Error-proofing
Performance measurement	Productivity Safety Installation cost Delay	PPC, CR, SV, QA/QC, RA, RS, and others
Planning classification (colored stickers)	By areas and discipline	By trades
Learning	Knowledge management (IWP)	Analysis of Frequency of plan failures 5 Whys, Plan–Do–Check–Act, detect–Correct–Analyze–Prevent Variance analysis Reason for variance

The literature was used in this study to compare two concepts that aim to improve the performance of construction production systems, which are AWP and Lean Construction. The analysis of the found studies showed that despite the differences in the approach, context and principles, type of projects, and structure and roles, the two concepts have many things in common. Which shows room for mutual interaction and integration between the AWP and Lean Construction. Figure 3 shows the possible integration chart between AWP and lean construction.

More specifically, AWP and lean construction share the goals of creating improvements in productivity, quality, and efficiency in construction projects. Both focus as well on the removal of all constraints that may hinder the flow of work and affect efficiency. The safety of workers and stakeholder participation in the planning and control are also among the shared points between AWP and lean construction.

Concerning how AWP can benefit from lean construction, one of the primary focuses can be more oriented toward the human factor. In lean construction, respect for people is an essential principle that is reflected in most lean tools; especially in the LPS. This principle requires respecting the inputs of workers, building trust, creating effective communication strategies, and strengthening the team working environment. Additionally, AWP can benefit from other lean principles such as the focus on flow and waste elimination and pull planning. Moreover, while AWP has its tools to improve the learning process, there is still room to benefit from the continuous improvement experience in lean thinking. Concerning performance measuring and control, focusing on the value of the client may help to produce more key performance indicators (KPIs) that can help achieve better performance on different levels while implementing AWP. Finally, AWP can benefit from the integration with other concepts related to lean such as TVD, IPD, and LPDS.

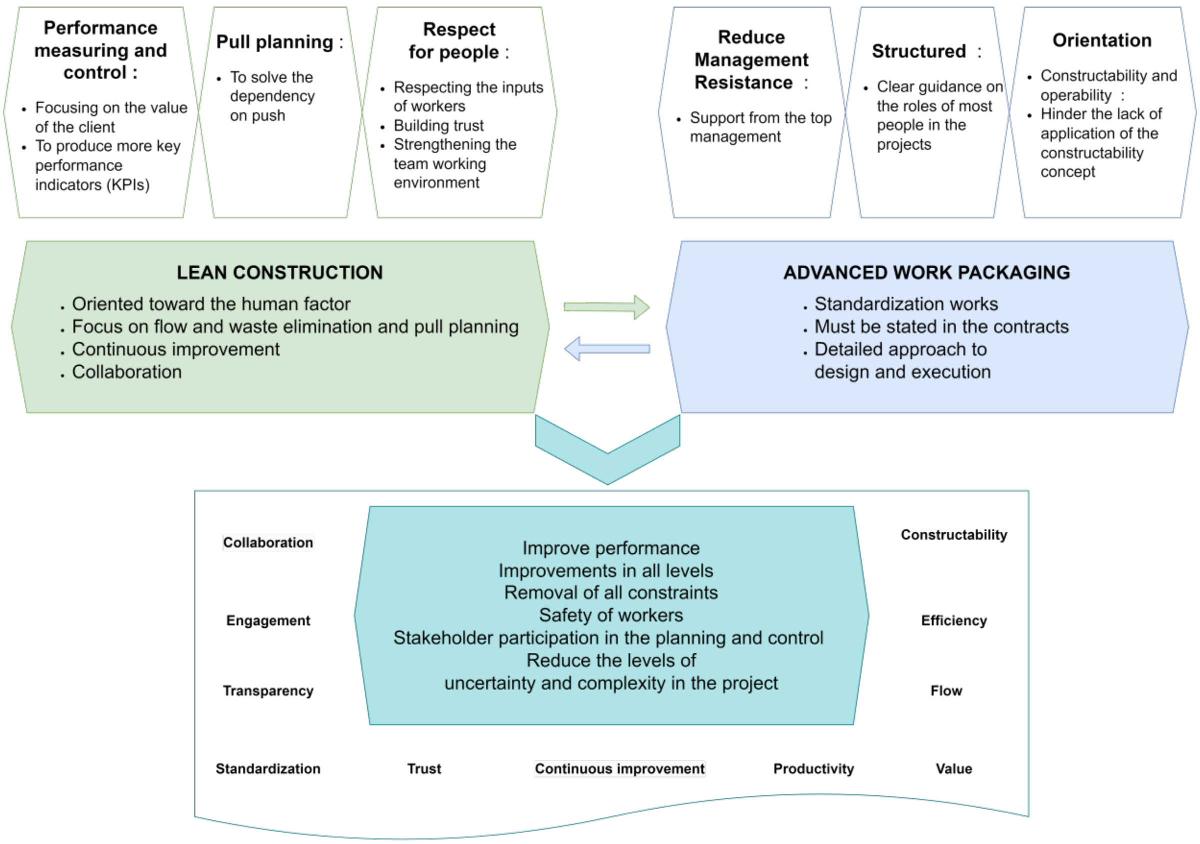

Figure 3: Possible integration chart between AWP and lean construction.

In turn, AWP can support the standardization works in lean. With its structured way, AWP offers opportunities for ease of implementation. This is supported by its clear guidance on the roles of most people in the projects. As a result, this might be helpful to face the challenges of the reluctance of people to adopt lean (Albalkhy et al., 2021; Albalkhy & Sweis, 2021). Additionally, as AWP has to be clearly stated in the contracts, its adoption with lean construction may help to reduce the management resistance to change and the lack of support from the top management, which was considered in many studies among the most serious barriers facing the adoption of lean (Albalkhy et al., 2021; Albalkhy & Sweis, 2021). Moreover, with its detailed approach to design and execution and its orientation toward constructability and operability, AWP adoption may hinder the lack of application of the constructability concept, which is another cited barrier that faces the adoption of lean (Albalkhy et al., 2021). Finally, as a method that was specifically developed for a large-scale project, the integration of AWP and lean construction can help to reduce the levels of uncertainty and complexity in the project.

DISCUSSION AND CONCLUSIONS

The integration of AWP and Lean Construction has the potential to create a more collaborative and efficient environment in construction projects, leading to improved project outcomes, reduced project delays, and cost overruns. The synergistic effect of integrating AWP and Lean Construction can promote standardization, constructability, and the adoption of best practices, leading to improved project outcomes. The integration can also promote the flow of work and value in the project and achieve continuous improvement through the use of lean tools and techniques.

However, the study has some limitations. The low number of publications about AWP in comparison to Lean Construction resulted in relying on non-peer-reviewed industry reports as a primary source of information on AWP. Further investigations based on case studies analysis, content analysis of the reports and standards of AWP compared to lean literature, or collecting perspectives via interviews, surveys, or any other data collection method may be required to investigate the possibilities, impacts, or challenges facing this integration between AWP and Lean Construction. The study does not focus on the detailed approach in AWP and a specific Lean tool such as LPS, rather, it covers the main themes of the work. Future studies can provide a comparison on the base of details in each phase of the project.

In summary, the study helps practitioners and researchers to understand the links and differences between AWP and Lean Construction concepts and how to integrate them to make improvements in the construction environment. The integration of AWP and Lean Construction represents a promising avenue for improving construction project outcomes, but further research is required to validate the impact of the integration on these measures.

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MEASURING TIME SPENT IN VALUE-ADDING WORKSPACES USING SMARTWATCHES

Cristina T. Pérez[1], Stephanie T. Salling[2], and Søren Wandahl[3]

ABSTRACT

This study addresses the lack of procedures for automatically measuring the share of time that construction workers spend on value-adding activities as a way to automate the work sampling technique. While previous studies aimed to automate this technique by focusing on activity recognition using sensors or video-based technologies, this research is concerned with identifying workers' locations on job sites using location-based sensors embedded in smartwatches. For this, the authors conducted a case study, which aims to measure the share of time workers spent in different outdoor workspaces. The study was carried out on a renovation project and involved five steps: (1) clarifying the workspace categories (production, preparation, and transportation); (2) data collection of carpenters' locations using geographic data points collected by smartwatches during 7 days; (3) data extraction and data aggregation; (4) data cleaning; and (5) data analysis using a Python script to automatize the classification of the data points into workspaces. The main contribution is a visual tool to visualize workers' positions on the job site in 2D. This information can be useful to indicate how many hours per day they spend in different workspaces and to understand the nature of a given construction activity.

KEYWORDS

Work flow, workspaces, smartwatches, digitization, visual management.

INTRODUCTION

Tracking of resources can be useful on construction sites for different purposes, and the topic has gained increased attention in research in recent years. Several studies have adopted sensor technologies for location tracking of workers and construction equipment to monitor health and safety (e.g. Awolusi et al., 2018), and others have focused on on-site logistics (Nasr et al., 2013). Resource tracking has also been applied with the intention of analyzing on-site productivity (Zhao et al., 2019).

Despite these recent efforts on tracking resources, data on progress and productivity are still mainly being collected manually on construction sites, either verbally in meetings, through weekly routines such as job site walking rounds, or by performing activity analysis or Work Sampling (WS) studies (Teizer et al., 2020; Zhao et al., 2019). The WS technique quantifies shares of time using a set of activity categories, classified into the Lean activity categorization of Value-Adding (VA) and Non-Value-Adding (NVA) activities. Though the WS technique is widely applied and acknowledged, it has been criticized for its snapshot-based approach and

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workflow interruptions of participants due to the presence of the observer on-site (Dozzi & AbouRizk, 1993; Wandahl et al., 2022).

Several studies have applied sensor-based and video-based technologies as alternative approaches for overcoming WS shortcomings. Vision-based activity analysis requires single or multiple cameras for detecting and tracking resources as well as procedures for activity recognition (Liu & Golparvar-Fard, 2015). Sensor-based technologies enable the identification of measurement of workers' posture, motions, and location (Cheng et al., 2017). But, only a few studies demonstrate how a real-time tracking system can be applied to determine the share of VA activities of construction workers (Görsch et al., 2022).

Another study applied an indoor positioning system based on Bluetooth Low Energy (BLE) technology, estimating presence indexes, representing uninterrupted presence time of workers in work locations considered production workspaces (Zhao et al., 2019). The presence index applied provides limited information on whether workers engage in VA activities when being present in productive workspaces and do not provide accurate information on the share of VA time spent during workers' daily activities. Nevertheless, this study suggests that uninterrupted presence is strongly correlated with VA time and can, thus, be used as a metric for measuring productivity on the project level based on two basic assumptions: (1) if work gets interrupted, these interruptions are mostly NVA activities; and (2) if work is uninterrupted in the productive workspace, VA activities are likely taking place (although NVA can also happen in productive workspaces).

Continuing the approach from Zhao et al. (2019), Görsch et al. (2022) combined video data from head-mounted cameras and location data from indoor positioning via BLE technology to understand the time spent in VA when uninterrupted presence is detected by indoor positioning. The study contributes to knowledge that the share of VA time that takes place during workers' uninterrupted presence can be numerically quantified, bridging a more explicit connection between VA time assessment and presence time analysis in construction. Therefore, the research by Görsch et al. (2022) suggests that uninterrupted presence with higher thresholds can be used to predict the VA level of workers more accurately without relying on manual efforts to scan through video recordings.

Based on this brief introduction, there is an identified need to conduct further studies that associate workers' presence in different workspaces with VA time to overcome the aforementioned WS shortcomings. For this purpose, job sites can be divided into direct and indirect workspaces similar to the Lean activity categorization into VA and NVA activities. It is reasonable to assume that if a worker spends most of their time in indirect workspaces, e.g., an unloading area, they are conducting NVA activities. On the other hand, if a worker spends most of their time in a production workspace, e.g., a floor under construction, they are most likely to conduct VA work.

Newer types of wearable devices, such as smartwatches, can be equipped with a wide range of sensors and technologies; accelerometers, electrodermal activity sensors, and location-tracking, to mention a few. Most smartwatches use a Global Navigation Satellite System (GNSS), for instance, the Global Positioning System (GPS), to capture information about the location of the watch, which then can be used to calculate current and average travel speed and distance or presence time in work zones (Pérez et al., 2022).

This paper continues the approach by the present research team, initiated by (Pérez et al., 2022) to use the geographical location data of workers collected by smartwatches as means of activity tracking. This new approach complements the current body of knowledge by providing a source of evidence that can potentially increase the accuracy of activity tracking studies to understand the time spent on VA activities. The ongoing research project seeks to answer the following research question:

- *Research Question (RQ):* How can the share of time spent on VA activities be estimated based on geographical location-based data?

To address this question, the authors conducted a case study on a renovation project. To the authors' knowledge, no study has been made on the accuracy of the GPS data from smartwatches used on a job site. Still, previous studies have obtained confident results when using the watches in outdoor environments (Pobiruchin et al., 2017; van Diggelen & Enge, 2015). Therefore, the data is only obtained from outdoor locations in this study.

RESEARCH METHODOLOGY

The authors of this paper adopted Case Study (Yin, 2003) as the primary research strategy, as case studies offer flexibility for explorative and theory-building research in real-life contexts. The phenomenon of the study comprised construction workers' locations using smartwatches as a digital tool for collecting data. The real-life context is represented by the building project studied.

CASE STUDY DESCRIPTION

The Case Study was conducted on a building renovation project in Roskilde, Denmark. The construction project consists of renovating 24 five-story buildings, totalizing 597 housing units (Figure 1). Four buildings were under renovation during the period of this case study, and these were named Building A1, B1, C1, and B2 (Figure 1a).

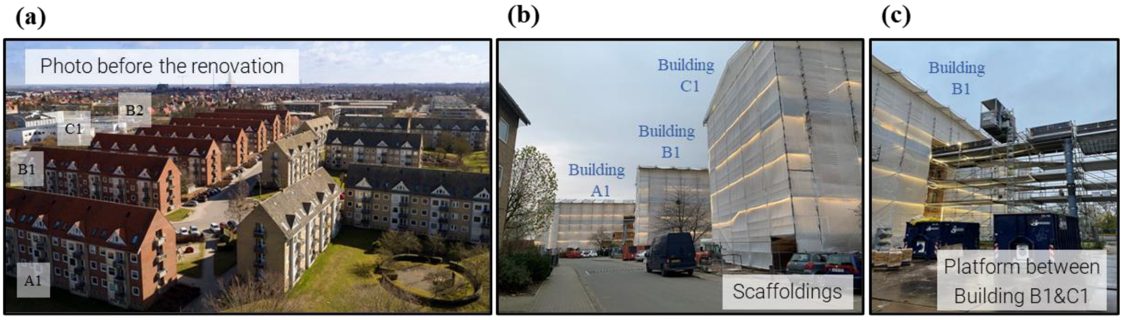

Figure 1: Job site of the case study: (a) before the renovation; (b) scaffolding used for covering the buildings; and (c) platform used to connect scaffoldings.

The main renovation tasks were related to external carpentry work, such as replacing windows and roofs. Installation of new ventilation, installing new electrical systems, and painting of the hallways represent the only three internal renovation activities. During the execution of the renovation project, most of the renovation activities were conducted from a façade scaffolding outside the buildings (Figure 1b). Besides carpentry tasks, this included masonry and painting work.

The main contractor placed modular containers within the job site for storage, administration, and changing rooms. The main material storage area, destined for inventory deliveries, was located next to the administrative containers. The contractor rented a façade scaffolding with plastic covering the entire temporary structure for each building under renovation. The scaffolding of Buildings B1, B2, and C1 were connected to facilitate workers' movement between the buildings (Figure 1c). Moreover, a mobile crane was used for lifting windows in place.

RESEARCH DESIGN

The authors adopted smartwatches to collect the distribution of GNSS data points in different workspaces. The research design consisted of the following five steps (Figure 2): (1) clarifying the workspace categories; (2) data collection; (3) data extraction and data aggregation; (4) data cleaning; and (5) data analysis.

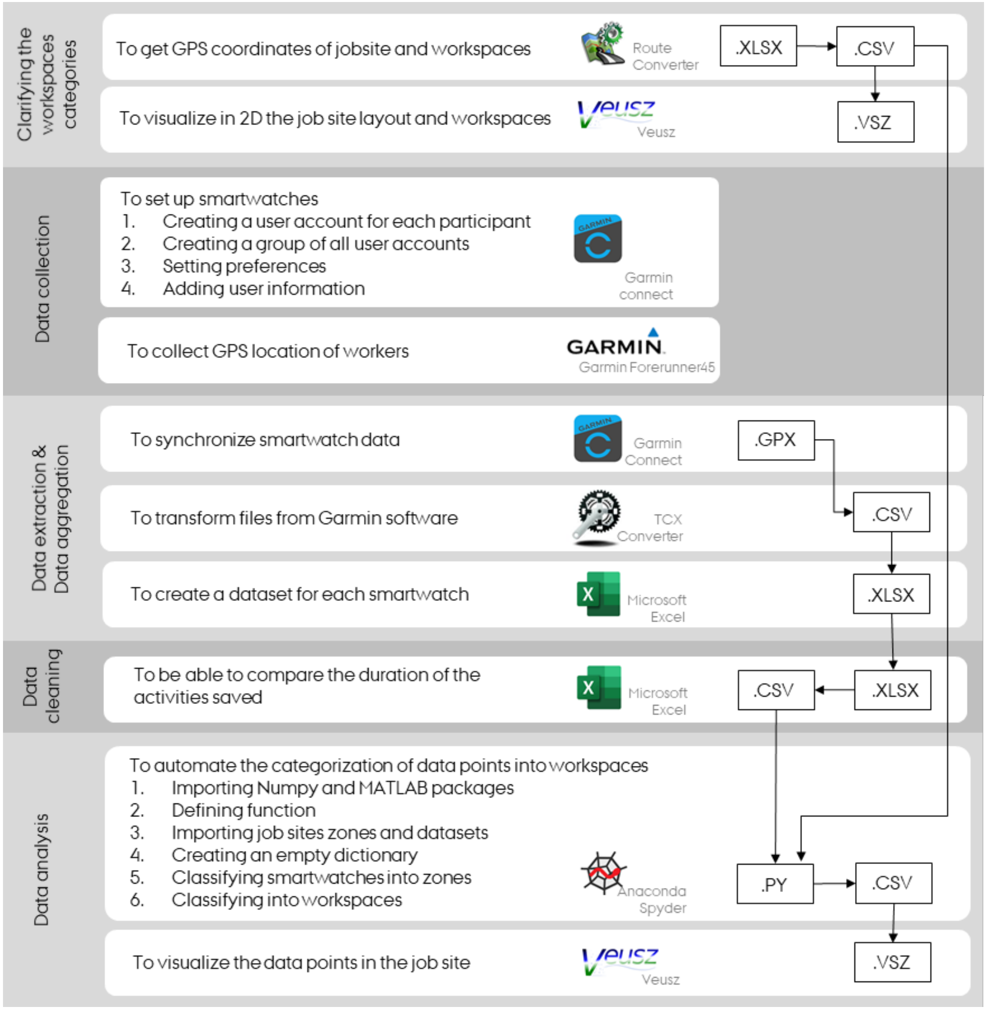

Figure 2: Research design.

Step 1: Clarifying the workspace categories

This study adopted the following workspace classification: (1) production workspace; (2) preparation workspace; and (3) transportation workspace. The production workspaces comprise the buildings under renovation and the scaffolding area. The preparation workspaces are represented by the area around all the buildings undergoing renovation at the time of data collection (Zone 1A and 1B in see Figure 3a), and the material storage area, where a dedicated preparation workshop was set up. The remaining parts of the job site are considered transportation workspaces (Zone 2A and 2B in Figure 3b).

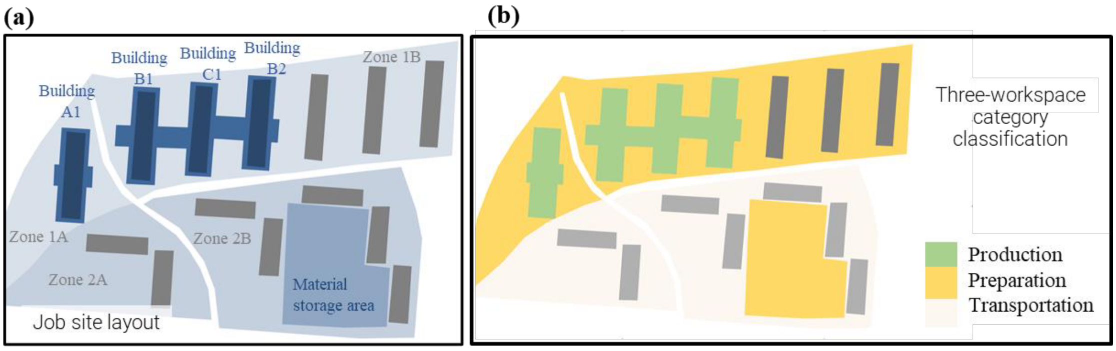

Figure 3: Job site: (a) description; and (b) divided into workspace categories

The authors collected the coordinates of the job site and workspaces using the RouteConverter program. RouteConverter is a GNSS tool used to display, edit, and convert routes from several different file formats (RouteConverter, n.d.). The list of data coordinates obtained from the RouteConverter was exported into a Microsoft Excel Worksheet (XLSX) file, converted into a Comma-separated Values (CSV) format, and then imported to Veusz. Veusz is a scientific plotting and graphing program (Veusz, n.d.). Veusz allowed the researchers to plot the data using a graphical 2D user interface for visualizing the job site layout divided into workspaces, cf. figure 3.

Step 2: Data collection

The data collection period lasted seven days (8.5 hours/each day) from 07:00 to 15:30, excluding breaks, totalizing 7.5 effective working hours per day. The seven days of job site visits were conducted in November of 2021. The research team adopted a stratified sampling approach for selecting the workers involved according to their tasks. Ten workers from the carpenter trade participated in the study. Each worker was associated with the serial number identification of each smartwatch.

The carpenters were equipped with a Garmin Forerunner45 smartwatch, which could collect the geographical location of the carpenters during their workday. This device provided the geographic coordinates using a combination of two GNSSs: The GPS and the GLONASS. The frequency of data point collection depended on whether a movement of the watch was detected and thus varied between one and 30 seconds. The preparation of the smartwatches involved four steps: (1) creating a user account for each smartwatch on the web version of the Garmin Connect app; (2) creating a group of all user accounts; (3) setting up preferences on the watches (e.g., notification settings, units of measure, GPS activation); and (4) adding user information (height, weight, age). Personal data policies hindered the collection of personal user information in this study. Consequently, general average data for a Danish male (Worlddata.info, 2019) was used as a substitute for the specific numbers. Lastly, to prevent data loss, the smartwatches were charged every night and synchronized after each day of data collection.

Step 3: Data extraction and data aggregation

The smartwatch data was synchronized to the Garmin web application (named Garmin Connect) using a USB cable. Since the devices have limited memory for storage, this functionality allows users to access historical activity data that can be used with other Garmin applications. The activity saved during the 8.5-hour workday was exported in a GPS Exchange Format (GPX) and then transformed into a CSV using TCX Converter program. TCX Converter program is a GPS data management solution for transforming files from different mapping software (TCXConverter, n.d.). For the purpose of the study, the authors exclusively used the following three features of each data point: (1) time; (2) latitude; and (3) longitude.

The data aggregation aimed to organize the three features of the raw data in a XLSX file to create a dataset over each smartwatch (named SW01 to SW10) for each day of collection (named Day 1 to Day 7). Due to various technical issues, not all activities were successfully recorded. The database contained 56 datasets, totalizing 188,180 data points.

Step 4: Data cleaning

For the data cleaning process, the main assumption considered was that to be able to compare the collected data, it must be uniform. The requirement established for this study was concerning the duration of the activity. In the same way as some activities were not recorded at all due to technical issues (e.g., the activity was stopped accidentally by the worker wearing the watch trying to look at the time), some were cut short in length or had large time gaps between the collected data points along the day. Activities with more than one hour of data missing were excluded. As only a low number of activities met the duration requirement on SW01, SW02, SW04, and SW09, the datasets from these smartwatches were excluded, leaving six smartwatches and 36 datasets for the analysis.

The remaining datasets were cleaned by excluding data from break times along the day. Moreover, only data within the official working hours (07:00 to 15:30) was included in the analysis. The data cleaning process reduced the size of the stored data from 188,180 to 115,072 data points, which is a reduction of 73,108 data points or 38.8% of the data.

Step 5: Data analysis

During the data analysis, the research team adopted Individual Participant Data (IPD) for a more appropriate analysis according to each participant's role. The main role and tasks of each carpenter of the six remaining datasets are: (a) Installing plastic frames for windows (SW03); (b) Installing windows from scaffolding (SW05); (c) Installation of windows and membrane on roof (SW06); (d) Installing wood boxes for ventilation pipes on the roof (SW07); (e) Grouting around windows and installing wood on roof after membrane installation (SW08); and (f) Foreman. Supervision activities and transporting materials from the storage workspace to their destination (SW10). The data analysis aimed to classify workers' positions into workspaces (Table 1).

Table 3: Summary of the collected data used for analysis.

Participants	Data sets	Total duration (h)	Data points SW03	Data points SW05	Data points SW06	Data points SW07	Data points SW08	Data points SW10	Total data points
6	36	270	26,983	26,199	16,607	17,014	13,063	15,206	115,072

To automate the categorization of each of the 115,072 GNSS data points from the 36 datasets into workspaces, the authors developed a script using Python scripting language. Python is a general-purpose scripting language (Python, n.d.). The authors used the Spyder IDE (Integrated Development Environment) version 5.1.1 bundled with the Anaconda package (64-bit version). The script includes six steps as illustrated in Figure 4: (1) Importing Numpy and MATLAB packages; (2) Defining zone function and smartwatches data points function; (3) Importing coordinates of the job sites zones and datasets; (4) Creating an empty dictionary; (5) Classifying smartwatch datapoints into zones; and (6) Classifying into workspaces.

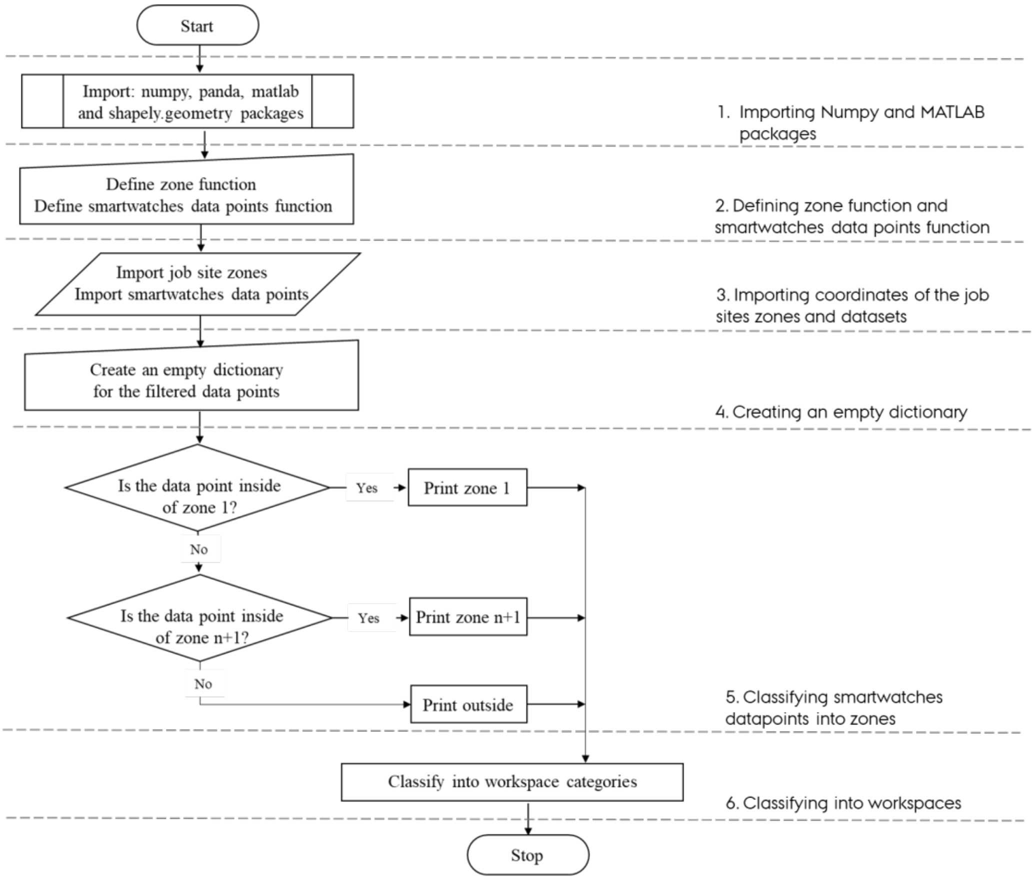

Figure 4: Flowchart of the process of classifying workers' positions into workspaces.

The authors also examined the distribution of data points within the job site using the Veusz program. Since the data points collected by the smartwatches are evenly distributed along the day, the number of data points in each workspace can be understood as the share of time spent in each workspace.

RESULTS AND DISCUSSION

VISUALIZATION OF THE WORKERS' LOCATIONS ON THE JOB SITE

The distribution of locations of the six participants in the smartwatch study from Day 5 to Day 7 of the data collection are illustrated in Figure 5. Each smartwatch is assigned a color of dots on the construction site maps, and each dot represents a data point. With more than 10,000 data points each day it is not possible to distinguish the points from each other or to analyze the watches individually, but the maps provide an overview of the places where the workers spent most time (i.e., the areas with the largest concentration of data points) and the paths they used when changing location. As expected, most of the time was spent in the area of the four buildings under renovation.

The overlapping of points from all the smartwatches in Figure 5 impedes an analysis of each worker individually based on these charts. For that reason, Figure 6 illustrates some examples of the distribution of data points on the job site when looking at only one worker at a time, in this case, the worker wearing SW06. It can be seen that the worker wearing SW06 spent most of their time in the production space of Building A1, walked between Building A1 and the material storage space using two different paths, and spent some time in the storage workspace.

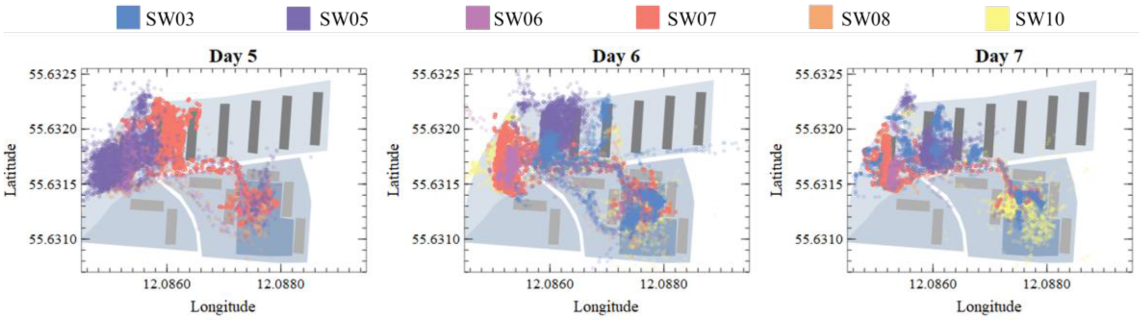

Figure 5: Workers' positions on the job site in Day 5, 6 and 7.

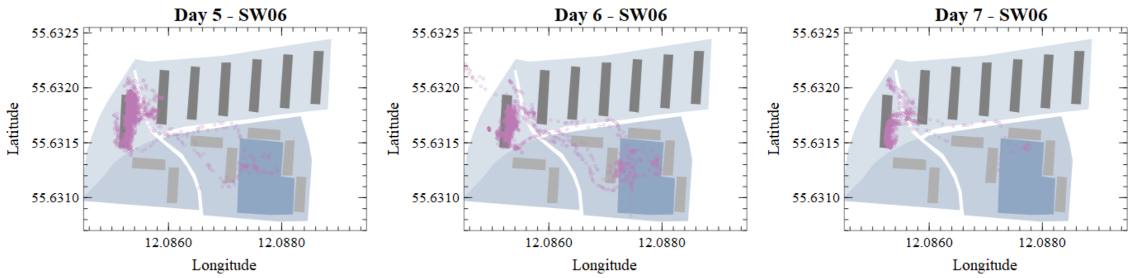

Figure 6: Positions of the worker wearing SW06 on the job site on Days 5, 6 and 7.

The visualization of workers' locations on 2D site maps can be used during planning meetings. These images are an objective way to visualize where workers spent their time during the week. Moreover, the visualization of the location of each worker helps to understand the places where each worker conducted activities. The 2D images can be combined with the location-based schedules to understand if each worker spent their time according to the planned location. So, the illustrations can allow trade supervisors and managers to solve problems and coordinate their work schedules, thus preventing minor issues from growing bigger.

WORKSPACE ANALYSES

Using the Python script, the authors classified the data points into a three-workspace categorization (Figure 7): (1) production workspace; (2) transportation workspace, and (3) preparation workspace.

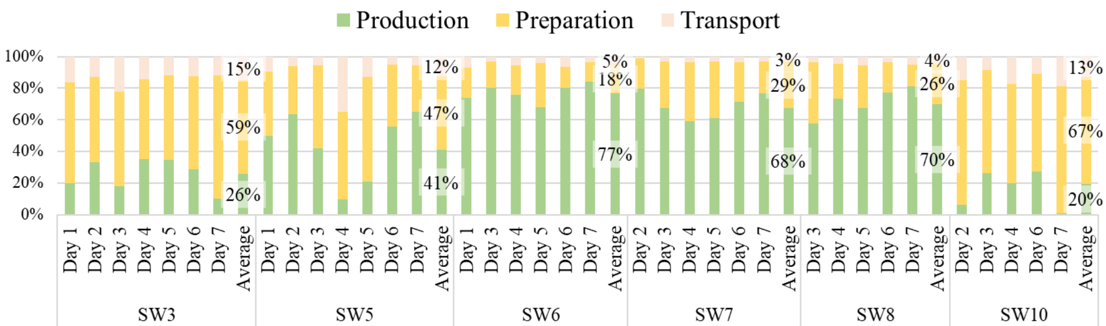

Figure 7: Distribution of data points in workspaces.

Thus, the Share of Time spent in Production workspaces (ST-Prod) represents the number of data points in the production workspaces divided by the total number of data points from that dataset, and likewise for the other two workspace categories. The distribution of data points in the different workspace categories as well as the standard deviation for each watch in each category, are summarized in Table 2.

Table 2: Classification of the GPS data points into workspaces for each smartwatch.

Workspaces	SW03	SW05	SW06	SW07	SW08	SW10

Production	6,995	10,674	12,726	11,486	9,126	2,983
Preparation	15,944	12,316	3,014	4,995	3,370	10,244
Transportation	4,044	3,209	867	533	567	1,979
Avg. ST-Prod (%)	26% ± 10	41%± 21	77%± 6	68%± 8	70%± 9	20%± 12
Avg. ST-Prep (%)	59%± 9	47%± 14	18%± 6	29%± 8	26%± 9	67%± 9
Avg. ST-Trans (%)	15%± 4	12%± 11	5%± 2	3%± 1	4%± 1	13%± 4

This study's main managerial contribution is identifying workers' locations recorded by smartwatches and grouped in predetermined workspaces (production, preparation, and transportation) representing different VA and NVA categories using scripting language. Although presence in production workspaces is not equivalent to time spent on VA activities, it is a prerequisite (Zhao et al., 2019). Hence, the information gathered about the share of time carpenters spend in different workspaces can be useful for several purposes. Two examples are presented as follows:

First, to indicate how many hours per day the workers spend on different tasks. For instance, considering the carpenter who was in charge of installing membrane on the roofs (carpenter wearing SW06); spent on average 5.78 hours in production workspaces (77% of 7.5 hours, see Tabæe 2), 1.35 hours in preparation workspaces (18% of 7.5 hours), and 0.37 hours in transportation workspaces (5% of 7.5 hours). According to these percentages, the authors can assume that the carpenter of SW06 spent almost three-quarters of his time doing VA activities, although being in a productive workspace does not exclude conducting other NVA activities. Another interesting example can be discussed by looking at the foreman (worker wearing the SW10). The foreman did not spend much time in the production workspaces, rather he walked around in the preparation workspaces around the buildings and spent most of his time in the storage and office area, which is defined as a preparation workspace. He spent, on average, 1.50 hours in production workspaces (20% of 7.5 hours, see Table 2), 5.03 hours in preparation workspaces (67%), and 0.97 hours in transportation workspaces (13%).

Second, to understand the nature of the different tasks conducted by each worker in a given construction process. It is well known that construction processes using prefabricated and off-site methods present a smaller share of time on VA activities on the job site and demand more time on NVA activities, such as preparation and transportation activities. An example of this can be seen observing the worker wearing SW05 in charge of installing prefabricated components, such as the windows (Figure 8a).

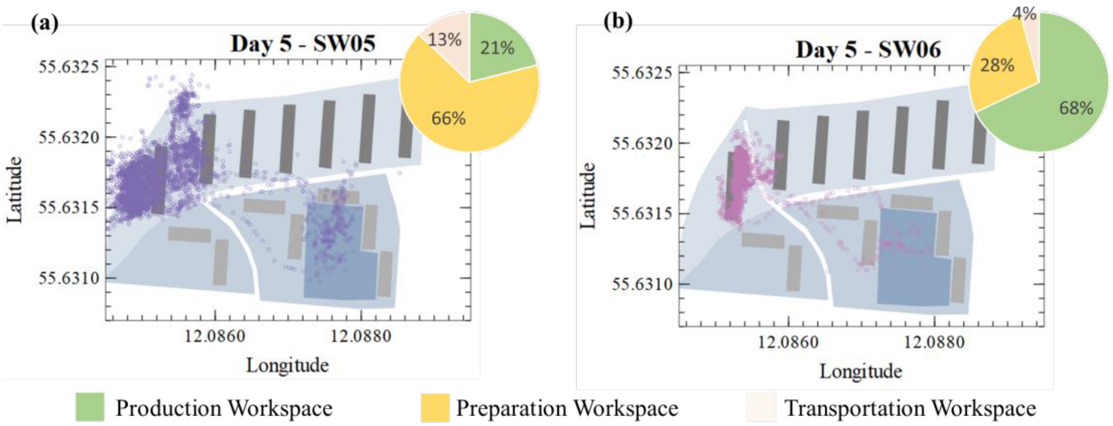

Figure 8: Distribution of points for the workers wearing: (a) SW05; and (b) SW06.

On Day 5, this worker spent 66% and 13% of his time in preparation and transportation workspaces, respectively. In contrast, the worker wearing SW06 was in charge of a highly on site-dependent activity, namely installing the membrane in the roof (Figure 8b). This activity involved measuring the membrane with a ruler, cutting the membrane with a knife according to the appropriate length and stapling the membrane, among other activities. Hence, on Day 5, the worker wearing SW06 spent 68% of his time in production workspaces, significantly more than the worker wearing SW05. So, the implementation of prefabricated components on the job site increased, among other factors, the time spent in NVA workspaces. This should be taken into consideration when conducting WS studies on job sites to align expectations with the applied construction processes.

CONCLUSION

This study addressed the lack of procedures for measuring the share of time that workers spend on VA activities automatically as a way to automate the WS technique. While previous studies have aimed to automate this technique by focusing on activity recognition using sensor-based or video-based technologies, this research is concerned with identifying workers' locations on the job site using smartwatches.

The research question formulated to serve as the guidance of this research was: How can the share of time spent on VA be estimated based on geographical location-based data? To address this question, this research conducted a case study. The results of the case study allowed the authors the identification of workers' time spent in VA workspaces (production workspaces) based on the GNSS data points collected by smartwatches worn by the carpenter trade on a construction site. Using scripting language, the workers' locations recorded by smartwatches were grouped into predetermined workspaces (production, preparation, and transportation) representing different VA and NVA categories. In this way, the information gathered about the share of time workers spent in VA workspaces, along with other information from additional sources, can indicate how many hours per day they spend on VA activities. Thus, the main contribution of this study consists of a novel approach using smartwatches to measure workers' distribution of time in workspaces. Smartwatches present a low-cost and scalable way of measuring presence in outdoor locations on construction sites.

This main limitation of this study is related to the workspace categorization employed for classifying data points. The authors adopted a three-workspace classification. The categorization of some places into one category or another may have impacted the distribution of time analysis. An example of this is the categorization of the scaffolding platform connecting some of the buildings as preparation workspaces. This workspace could have been categorized as a transportation workspace from another point of view. Future studies should adopt regression testing to verify which kind of category fits better for each workspace. Moreover, other zones can be used for the classification of the job site, such as the Location Breakdown Structure which uses location-based schedules.

Lastly, this study raised topics to be examined in greater depth in future research efforts, e.g., analyzing the utility of acceleration of watches to detect VA and NVA work. In this study, workers' locations were collected using smartwatches as the only source of evidence. To improve validity, future studies should collect data about the share of time spent in different workspaces from additional methods, such as the WS technique, questionnaire application or video analysis. Moreover, future studies could compare the locations collected using a GPS tracker or mobile phone with the locations collected by the smartwatches.

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A KAIZEN EVENT ENABLED BY SYSTEM ENGINEERING IN AN INFRASTRUCTURE PROJECT

Matt Stevens[1], Ali Eghbaljoo[2], and Frans Thevissen[3]

ABSTRACT

A Kaizen Event is a well-defined and accepted approach to construction outcome improvement. However, rising project complexity is making this a very involved process if it is to be successful. System Engineering (SE) is an emerging practice that can address project complication. This paper will share a journey of a SE team on how to streamline sophisticated internal processes that manifest in better safety, quality and productivity when improved. SE is a recent innovation emerging as an essential discipline considered state-of-the-art. It crystallises the integrated processes of work and their outcomes on projects and allows constructors to standardise their best practices effectively. This case study of a mega infrastructure rail project in Australia is a relatively brief treatment of a complex process, its factors and its results.

The project work package delivery was improved, including lower cost, as they were sequentially built. For the future, rapid urbanisation and climate change effects are increasing in Australia, and contractors must respond efficaciously for all stakeholders for the greater society to benefit. Mastering Lean principles such as Kaizen Events can help mitigate or minimise long-suffered construction industry problems.

KEYWORDS

Lean construction, SESA, system engineering, kaizen event, continuous improvement

INTRODUCTION

This case study explores and examines the multistep process to significantly improve delivery involving four projects. The paper's research question is, 'Has the application of Kaizen Events improved the SE processes in this megaproject's sequentially scheduled work packages?'

RISING PROJECT COMPLEXITY

A high degree of internal and external complexities has caused many difficulties in construction and hindered the successful delivery of mega-construction projects (Kardes et al., 2013). Common evidence is that significant differences exist in the performance of different types of large construction projects; for example, according to Flyvbjerg (2014). the average cost overrun rate for rail projects is 44.7 per cent, whereas for road projects are 20.4 per cent. Systematic understanding and effective control for complexity are crucial components of project management (Bosch-Rekveldt et al. 2018)

Fast-Berglund et al. (2013) assert that construction complexity positively correlates with installation errors. In mega construction projects, many errors may occur during the construction process due to the complication of multiple technical and management process streams. The accumulation of such errors will lower the overall quality of the project and might even affect the function and operational efficiency of the project. A well-accepted stability theorem (May–Wigner) concludes that increasing system complication inevitably leads to chaos (Sinha, 2005). Aslaksen 2008 concludes that construction project complexity has increased due to several factors such as material science, equipment utility and value (both installation and facility), and design along with increased government regulations.

INCREASING CONSTRUCTION NEEDS

Rapid Urbanisation

Urbanisation is a manifestation of improving human society and economic development; it is critical for social and economic development (Gong 2022). The 21st century is one of urbanisation. Along with this phenomenon, the world's population will increase. White et al. assert (2010) that lifestyles are also changing in the 21st century. As a result, people will demand larger dwellings and other facilities. The three phenomena together point to a need for construction that may outpace contractors' ability to meet it.

Climate Change Effects

The increased consistency, duration, and severity of high-temperature weather have increased recently due to changes in climatic conditions. Australia is highly vulnerable to this hazard. A growing number of studies in Australia have been conducted each year over the last decade related to the heatwave phenomena (Pörtner et al. 2022). Dealing with heat would require upgrading current buildings and other structures, thus, further increasing construction demand. Due to climate change, chaotic weather events such as wildfires, storms and floods will increase the destruction of the built environment. Eingrüber and Korres (2022) assert that the speed and intensity of flooding will accelerate with climate change. There is a high probability of increased and erratic rainfalls accompanied by higher winds in many parts of the world (Moradkhani et al. 2010). Climatic causes play a prominent role in the deterioration of building fabric, and climate change is projected to accelerate the built environment deterioration rate (Johns and Fedeski 2001). The International Panel on Climate Change (IPCC) asserts that costs for maintenance and reconstruction of urban infrastructure, including building, transportation, and energy, will increase with global warming (Pörtner et al. 2022)

KAIZEN EVENT

The factors that guide a Kaizen Event, the continuous improvement of processes, were introduced based on presenting a scientific model for implementing improvements founded on a sequence of questions that enable identification, analysis and problem-solving, called the Scientific Thinking Mechanism (Shingo 2010). Furthermore, Imai (1996) asserts that kaizen implementations to result in practical solutions is based on three general activities: evaluating data, communicating problem-solving methods and keeping the Kaizen Event culture active. Specifically, Kaizen is an intensive Step Change process improvement where the team focuses on improved methods of perfecting execution. It occurs in eight intensive steps enabling this greater efficacy:

1. Choose the theme/focus of the application (determined according to administrative policies according to priority, importance, urgency or economic situation);
2. Analyse the context;
3. Collect and analyse to identify the root cause;
4. Establish countermeasures based on data analysis;
5. Implement countermeasures;
6. Confirm the effects of countermeasures;
7. Establish or revise standards to prevent recurrence;
8. Review the previous processes and start working on the next steps.

SYSTEM ENGINEERING

The International Council on Systems Engineering (INCOSE) defines SE as "an interdisciplinary approach and means to enable the realisation of successful systems.". Blanchard (2004) more succinctly stated that it is an orderly process that brings a system into being that integrates humans, materials, equipment, tools, information, technology, and money to function in delivering a specific outcome. Johansen and Hoel (2016) define Systematic Engineering as "an assurance that the project fulfils all functional requirements within the set time, cost and quality requirements, planned and verified by a structured process managerially driven from design and planning to handover". However, there is little documentation by the industry and light research by academia to understand the performance of practitioners and the product (Beste 2020).

In the implementation in the construction industry, the need for System Engineering (SE) is becoming greater since construction project complexity is increasing (Aslaksen 2008); its economic value is growing to USD 15.5 trillion worldwide in 2030 (Pacheco-Torgal 2020) and failing to consistently deliver projects to the satisfaction of the project owner and end-user (Boyd and Bentley 2012). Raworth (2017) asserts that all industries need to be "savvy with systems" to succeed in the 21st century. Therefore, the economy's common understanding needs to be updated from its pre-millennium knowledge to one of the complex current systems of many interdependent parts SE can rapidly and reliably integrate business and technological processes that construct infrastructure, building and processing facility projects (Aslaksen 2008).

Constructing the built environment involves many complicated tasks that must be carried out with extreme care while economising on costs. Most construction project functions are costly, and even a minor mistake can cause significant financial liabilities. Therefore, a steady and careful management process is required (Lu et al. 2013). In this case study, SE was executed on an existing process and did not have the luxury of a legacy-free or "green field" operation. Lynghaug et al. (2021) note that manufacturers pursue SE to improve a product or process. Once embedded, the improvement is produced in high volumes. In the construction sector, design and construction efforts are spread across project stakeholders, often one-off actions that result in lessons learnt that are usually minimally captured.

Beste (2020) proposed further studies of SE with more data from an international perspective to complement the existing research and improve the discipline. Furthermore, it is critical to understand many stakeholders' views, such as the design team, contractor and customer, to increase the clarity of the dynamics.

There exists a high conflict level in the construction industry. Reasons for this conflict include delays, cost overruns, and quality problems. The unreliability of multifactor productivity and these factors might be interrelated (Lynghaug et al. 2021). They also note that the implementation of the Systems Engineering methodology is highly dependent on the level of competence among employees in the projects in which the interdependence of tasks is disrupted by a lack of conscientiousness and industriousness by a worker(s)

As the construction effort starts with designing the work of co-dependent but standalone companies (i.e., contractors-main and sub, suppliers and designers), Lynghaug et al. (2021) assert that in practice, SE performs as a Systems-of-Systems improvement process, creating a methodology in which stakeholders work interdependently to accomplish the complex task of delivering better safety, quality, cost, schedule and sustainability. Axelsson et al. argued that the lack of a Systems-of-Systems approach is a significant reason construction productivity has stagnated. The roots cause seems to be a focus primarily invested in the resilient design of the standalone infrastructure constituent parts rather than how infrastructure components can be integrated to comprise a dynamic and valuable system (Vora et al. 2017)

The V-model is well-recognised in Systems Engineering. The approach moves a re-engineering review through design and decomposition subcomponents such as concept analysis, functional analysis, and design synthesis. In the second half of its sequence, satisfying integration, verification and integration, including operation and maintenance requirements of the completed project, is its focus (Elm et al. 2008, Beste 2020). See Figure 1.

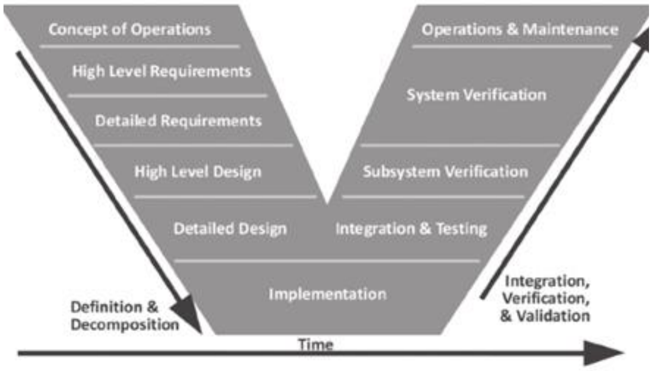

Figure 1: The V-model is the Core Framework Utilised in System Engineering (Elm et al. 2008)

Lynhaug et al. (2021) found problems with verification and verification (V&V) related to ambiguous technical and business specifications. These ill-defined requirements are partly blamed on the lack of budget and time for V&V activities in the early phase—subsequently, this lack of clarity results in imprecise contract language, schedule delays, and verification failures. Cotterman et al. (2005) assert that there are five general factors to consider in system engineering. They are 1) Concept of Operations 2) Business Case 3) Best Practices 4) Standards and Regulations 5) Lessons Learnt.

The term, System of Systems (SoS) was created decades ago to crystallise a definition for an approach to execute complicated projects such as construction infrastructure. Its attractiveness is that it combines disparate functions synergistically towards a common goal. However, SoS engineering has to be customised to individual complex ventures due to their independence, heterogeneity, evolution, and emergence factors. (Nielsen et al. 2015, Lynhaug 2021). Clark (2009) asserts that SE synergises the value of the components when:

1. the elements are integrated (i.e., have interfaces)
2. these elements might be (or not) members of a common domain (such as a product line or rail project)

CASE STUDY

Dozens of highly similar infrastructure projects were procured and scheduled in Australia, starting in 2016 and planned to continue until 2025. Due to their nature and limited resources, they were sequentially constructed, allowing for robust implementation using a continuous improvement approach to spur innovation. This case study is based on similar rail projects – two current and two future states.

MOTIVATION

The stakeholders found that after finishing their first two infrastructure projects as part of this Alliance Contract, the mega project's system engineering and safety assurance processes were inefficient and unreliable. A traditional Kaizen effort could not succeed in several areas without a more sophisticated approach. Upon inspection, they were found to lack communication clarity and process annunciation. Examples include a lack of defined roles and responsibilities, resulting in unpredictability, waste, and program risk. The Project Director stated, "The system engineering and assurance process (system, outputs and definition) is inefficient and lacks defined roles and responsibilities for alliances developing rail infrastructure projects resulting in uncertainty, waste, and program risk."

METHODOLOGY

A re-engineering initiative was started under the System Engineering and Safety Assurance (SESA) team which included the preparation and review of Safety Assurance Reports (SARs) and Safety In Design (SID), risk/hazard identification, mitigation & management throughout the project life cycle. This paper will refer to it as System Engineering or SE. Requirements management, including Requirement Allocation and Analysis Traceability Matrix items (RAATM) for the asset delivery's complete 'V' cycle. System interface and integration management, including Human Factors and other key systems' integration in design development and risk management support.

The focus was on improving the next two projects in the scheduled sequence. To launch the process, a 1-day Kaizen Event workshop was planned and followed by short discussion sessions with the core team to facilitate breakthrough events and manage the transition from the current state to the future. As a result, on multiple projects implemented the desired future state. The stakeholders formed a SE transformation team to examine the performance of two rail infrastructures, labelled Project 1 and Project 2, with explicit instructions to audit practices, analyse results and recommend improvements. Information organisation was critical for the team to effectively and efficiently learn, implement, and monitor the lessons learned from the first cohort of projects analysed. Also, they had to annunciate and discuss their calculations and assumptions to benefit from a discussion.

The V-Model lists many generalised tenets of the projects, such as "Operations" and "Design" factors - See Figure 1. Table 1 contains the ratios to compare these four projects accurately.

- The SE cost is a combination of the Joint Venture, Designer and End-User costs
- Total cost is critical to calculating to form accurate measures, including ratios relating to worker hours, general and administrative expenses and return-on-investment
- The projects initially analysed Project 1 and Project 2 had a similar scope of work for the SE team. It is critical to have similar work packages for a creditable improvement comparison.
- SE team spent more time on Project 1 than Project 2 to set up initial processes and form the team (assumed an add of 30% - the first three months with more management time). Initial set-up is a one-time expense that should be removed from the first project or proportionally expensed to all projects.
- A weighting system was calculated and applied to other work packages to enable the team to compare the SE cost to Project 1 and Project 2 average when the scope of work was different (e.g., Project 3 compared to Project 2 ratio is 1.05; staff room added 5%, set up a time with V/Line (the State-Wide Rail Operator) added 5%, Signalling upgrade added 5%, package value -10% impact)
- The weighted cost of the SE team on Project 3 was 0.749% of the AOC (0.419% less than Project 1 & Project 2 average)
- The weighted cost of the SE team on Project 4 was 0.864% of the AOC (0.303% less than Project 1 & Project 2 average)
- The average weighted cost of the SE team on Project 4 and Project 3 was 0.361% of the AOC, less than Project 2 and Project 1 average

- The designer cost used in the model is based on the invoiced figures. However, the cost of Designer and Asset Owner cost is estimated assuming a $150 hourly rate for managers and $120 for other resources that bill out at 160 hours per month

SE was the chosen approach since changing administrative projects to a more precise (and tedious) one would cause the comparison to be suspect. The project leaders commissioned a group of SMEs to jointly assess the percentage to increase or decrease for variations from the baseline projects. This multi-professional integrated approach has been proven to evaluate differences and estimate impacts more accurately for individuals working alone.

Table 1: Component Coefficients to Compare Projects Against Baseline Determined by the Projects' SMEs

Ratio Criteria	Ratio %	Project
Initial Set up/Team forming	+30%	Project 1
V/Line set up	+5%	Project 3
Not connecting to the existing line	-15%	Project 4
Car park	+15%	Project 4
Staff room	+5%	Project 3
No Line upgrade	-10%	Project 4
Signalling upgrade	+5%	Project 3
Greenfield	0%	Project 3
Scope change	+30%	Project 4

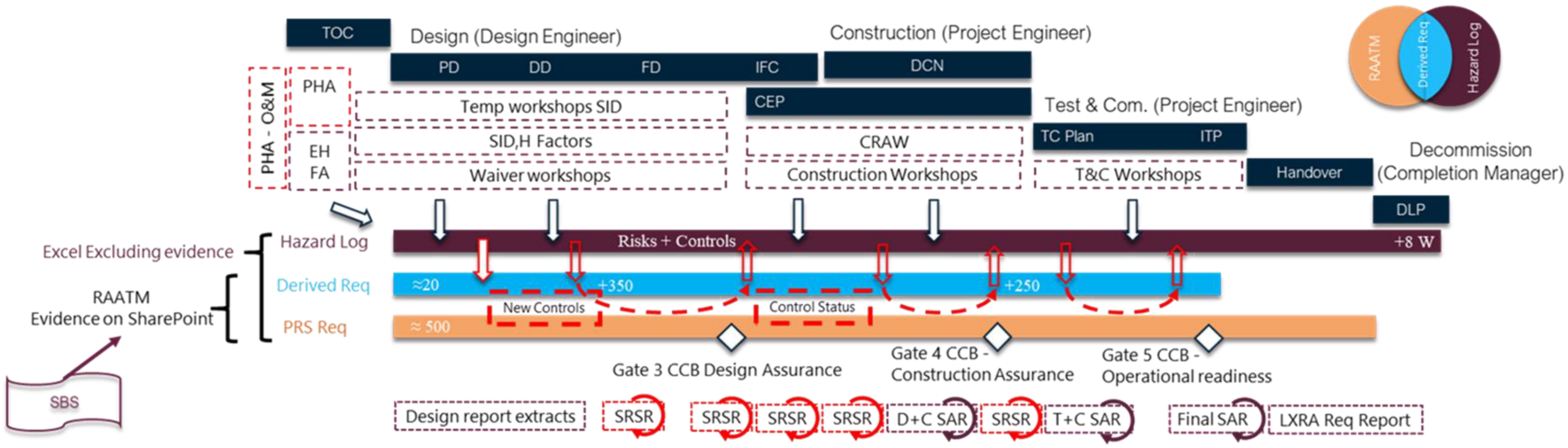

Figure 2: Current State of Projects 1 and 2

Major Issues and Improvements Needed:

- Duplicated effort for evidence reporting and report compilation
- No single source of truth for derived requirements
- Construction Operation &Maintenance risks & controls not tracked in Hazard Log
- Hazard Log can't be amended
- Controls in Hazard Log are unclear
- Hazard Log not consulted when evaluating work packages
- No time/opportunity to act on partially & non-compliant requirements
- Hazard Log management is not continuous across Design & Construction
- Resource burns out

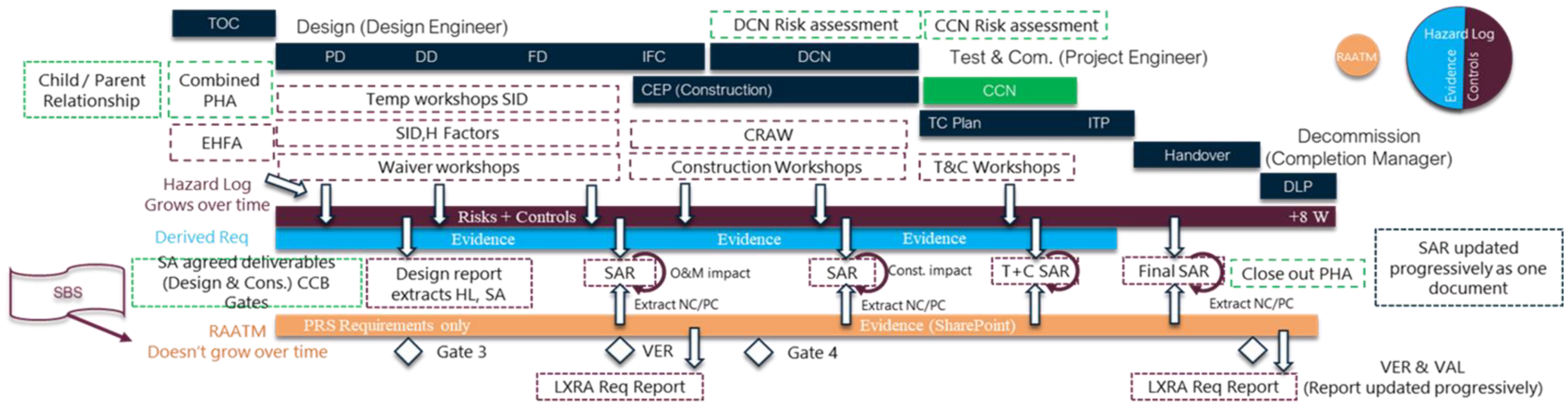

Figure 3: Future State Projects 3 and 4

CHANGES FOR IMPROVED (BEST) PRACTICES:

- Hazard Log, including reference to evidence. Complete information for others to work from – no rework
- Hazard Log progressively updated. Contemporaneous notes thus less error due to memory loss
- RAATM is used only for Project Requirements Specifications (PRS) requirements. A deeper understanding of governing standards for project
- Clear roles & responsibilities using the Responsibility, Accountability, Consultative and Inform (RACI) Matrix. Clear assignment of the lead responsible person who will deliver the task
- Combined Preliminary Hazard Analysis (PHA) workshops & reports. Two activities combined into one – more efficiency
- Visual Management Centre (VMC) for Short Interval Control. "One version of the truth" approach – less confusion and double-checking activity
- Progressive assurance through an extract of Hazard Log (SRSR). Documented quality documented at the time of confirmation.
- Focus on Unique & Novel Assets + Material + Construction Methods. Unfamiliar items and activities need more time upfront to increase cycle time when utilising
- Hazard Log consulted when evaluating projects. History is invaluable to the improvement of safety, quality and productivity

Table 2: Project Cost and Saving Comparison (AUD) – First Two versus Last Two Packages

Package	Actual Outturn Cost (AOC)	SE Cost	% of SE Compared to AOC - Weighted	Achieved Saving Compared to Projects 1 and 2
Project 1	$77,786,146	$1,191,900	1.179%	NA
Project 2	$72,556,966	$839,000	1.156%	NA
Project 3	$127,941,091	$1,006,100	0.749%	$535,527
Project 4	$90,186,517	$919,600	0.864%	$273,609
Total SE Difference Projects 1 & 2 and 3 & 4		**$56,400**		
			Total Saving	**$809,136**

BENEFITS

The alliance team recognised and articulated several benefits to the SE approach that they created and implemented.

- Significant reduction in resources required to manage SE processes once systematised.
- Less staff frustration and potential staff turnover due to the routine and familiarity of a system.
- High-quality safety assurance report (SAR) to improve asset owner's confidence in alliances; thus, the director may spend more time managing their organisation's everyday functions.
- Direct child/parent relationship with Project Hazard Authority making closing hazard list (hl) items easier.
- Eliminate duplication and thus increase process speed, higher asset utilisation and fewer costs.
- Eliminate or reduce project risks minimising schedule disruptions and unbudgeted costs.
- Standardised assurance report template making training, recording and analysis easier.
- Better utilisation of resources (less stressed equipment and safer crews). Since these inputs are always constrained, this can lessen switching between projects, i.e., Fewer inefficient start-ups, closedowns and transfers of people and equipment,

DISCUSSION

An intensive collection of information, including data and observations, is needed at the beginning of a Kaizen Event initiative in construction. In addition, SE requires data (qualitative and quantitative) and other information, such as an existing state process map, to be collected and analysed to transition between current to future states.

Where they exist, construction projects' trade and discipline-oriented silos lead to sub-optimal interfaces accompanied by verification and validation challenges. This was true in this case study. As is well documented, the construction industry differs fundamentally from the manufacturing domain, emphasising the differentiation of the product design – due to the customer need for a unique product due to local conditions such as the project's purpose, location, material availability, equipment selection and local technical mastery - rather than standardising process design in its engineering of systems effort.

The complexity is not only trade sequencing but also structure and services integration. Since products have increased sophistication than the skilled craft to install them, a new system conflict or unintended consequence may appear with the latest design. The process seems to require a review and possible update, just like a firm's strategic plan. The issue is which firms will re-engineer the design and construction process as their stakeholder groups constantly change. Prime contractors and project owners are in the hundreds in most regional markets. This issue suggests that Lean Construction researchers and practitioners must focus on the enterprise rather than the project as a starting point to accomplish the SoS approach that Nielsen et al. (2015), Lynhaug (2021) suggest.

SUMMARY AND CONCLUSION

According to Flyvbjerg (2014), rail construction has twice the risk of budget overrun when compared to road projects. This problem appears to signal the need for a detailed and holistic improvement approach to both. SE fits this requirement. The principle of Kaizen was utilised to streamline the SE process. This can be characterised as SoS. It is essential to point out that practices and insights will stay with the stakeholder firm for use again, while others are unique to the infrastructure project thus, not readily applicable to the next one.

Construction has many barriers to improvement and innovation. This may also be part of the reason that hampered many companies from developing this SoS approach. However, it is clear that an opportunity exists; this case study demonstrates that with the addition of a minimal cost (AUD 56,000) of targeted investment based on a thorough review, a significant saving (AUD 809,000) can be realised. Total savings on the portfolio of ten projects are predicted to be between AUD 5.8 and 7.1 million, due to be completed later this decade. For accurate outcomes, the SE team used the audited cost of the SE process and the resulting AOC after the completion of each package. At the time of publishing, a final result has not been finalised and announced.

Kaizen is a valuable process for long-term and consistent improvement. Tedious and tireless upfront work is needed to ensure a high probability of successful transformation in Mega Projects. Given the low margins and increasing complexity of construction, it appears to be a minimum requirement. With the impending dual crises of rapid urbanisation and climate change effects, it seems crucial to society's future.

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MASTER SCHEDULE OPTIMISATION WITH THE USE OF FLOWLINES AND PERFORMANCE DATA

Danny Murguia[1], Asitha Rathnayake[2], and Campbell Middleton[3]

ABSTRACT

In the UK construction industry, Gantt charts and the Critical Path Method (CPM) are the institutionalised and accepted tools for managing construction programmes. Together with the lack of a consistent measurement framework, little is known about current productivity levels and the opportunities for improvement. Using the case of four buildings in London, this paper aims to develop a strategy to optimise the duration of master schedules using real project data and optimised production rates. Data were collected during the structural works and translated into master-level flowlines. Key performance metrics were extracted: start-to-start duration (between levels), number of concrete pours per level, batch area, and production rates. The results showed a high spread of variability in performance within and between projects. However, higher production rates are associated with shorter start-to-start durations between consecutive levels, a higher number of slab concrete pours per level, smaller batch areas, and higher prefabrication levels. The results were applied to the building with the lowest performance. Increasing the number of slab pours would reduce the programme by 39% and increase the production rate by 65%. Whilst more performance data is required to build up a robust database, these initial findings can provide contractors and clients with evidence that there is room for improvement. A client was engaged during this research and is willing to prescribe flowlines and performance metrics in future projects.

KEYWORDS

Batching, flowlines, master schedule, performance, productivity.

INTRODUCTION

In 2013, HM Government issued "Construction 2025", an industrial strategy which sets outs how the industry, represented by the Construction Leadership Council (CLC), and Government *"will work together to put Britain at the forefront of global construction over the coming years"*. The strategy set out ambitious targets including 33% lower costs, 50% faster delivery, 50% lower emissions, and 50% of improvement in exports. The presumption in favour of off-site construction, new talent and skills, digital design and smart construction, low-carbon construction, industry growth, and leadership are the core pillars of this vision. A decade on, however, there is still no clarity on whether these targets are achievable or how much progress the industry and Government have made. The presumption in favour of off-site construction

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has triggered several demonstrator projects and industry and academic efforts to measure performance. For instance, Jansen van Vuuren and Middleton (2020) published data from 46 school projects with varied levels of off-site construction. However, this study revealed that the data does not provide conclusive evidence to establish a correlation between off-site construction and improved performance. Moreover, the authors argued that there is a need to rethink how performance is measured. Bassi et al. (2022) presented data from several off-site housing projects in Bristol. Whilst programme reduction was achieved, cost reduction was not accomplished due to the small pipeline of work for manufacturers; and it is expected that cost benefits will be achievable in the future. Thus, despite the ambitious targets, there is no evidence of ongoing performance improvement.

The Construction Productivity Taskforce (CPT) is a group of major UK clients, contractors, and consultants. The CPT aims at identifying and trialling new ways of making the construction sector more productive. The authors of this paper are working with the CPT to collect, interpret, and analyse construction data to set benchmarks, identify areas for improvement, and produce new knowledge on how the industry operates. Whilst some previous research have presented case studies of lean applications in the UK construction industry (Sarhan & Fox, 2012; Drysdale, 2013; Daniel et al., 2018; Tezel et al., 2018), the reality is that major clients and contractors are unaware or have little knowledge of lean construction techniques for production planning and control. As such, the current paper uses lean construction concepts and techniques to demonstrate the potential presence of waste in the construction process and suggest possible interventions that clients and contractors can make to achieve higher levels of productivity. The scope of this research is situated at the master planning level where clients and contractors negotiate the project duration and the interdependencies between work packages. Observing potential performance improvement at the master planning level is the first level where waste can be eliminated. Consequently, further layers can be observed and analysed at the activity level as presented in the companion paper (Rathnayake et al., 2023).

This research has collected performance data from four residential and commercial buildings in London. By using high-level strategies such as batching and master-level flowlines, data were analysed quantitively to determine the causes of variability in performance within and between projects, and to demonstrate the potential performance improvement that can be achieved. The paper is structured as follows. First, a brief background is presented. Second, the case studies are described including the type of data collected. Third, the results are presented and interpreted with an emphasis on master planning duration improvement. Finally, the results are discussed, and this is followed by conclusions and a description of future work.

BACKGROUND

LEAN IN THE UK CONSTRUCTION INDUSTRY

There is some evidence in the lean construction literature that lean techniques have been implemented in the UK construction industry, particularly in highway projects from the client perspective (Drysdale, 2013). For instance, Daniel et al., (2018) showed the effect of procurement methods in the Last Planner System (LPS) implementation whilst Tezel et al., (2018) presented the results of continuous improvement and visual management techniques. Daniel et al., (2017) investigated the adoption of collaborative planning (CP) as opposed to the LPS implementation among UK contractors. The study showed that collaborative planning is a method used by contractors to plan construction activities with subcontractors with a focus on programme and time compression. As such, it lacks several components of the LPS such as the make-ready process, look-ahead planning, constraint analysis, and consideration of flow and learning. Some previous studies (e.g., Johansen & Porter, 2003) argued that the LPS can be applied to UK building constructions after the consideration of cultural barriers. For instance, subcontractors have commercial pressures from Tier 1 Contractors and "push" planning takes precedence over production and continuous flow. Moreover, commercial managers do not fully vet subcontractors' production capability and there is little consideration of the relationship between price and performance. Sarhan & Fox (2012) confirmed that UK construction organisations are far behind in a comprehensive lean approach due to the lack of awareness and understanding and suggested that large public sector clients are ahead of adoption and can incentivise the rest of the industry. Regardless of the levels of adoption, there is a void in the literature regarding performance in the UK construction sector and how this can relate to partial or full, formal or informal, implementation of lean concepts. Thus, this study aims to collect evidence from construction projects and use concepts such as flowlines and batching to identify high-level process waste and areas of improvement at the master planning level.

FLOWLINES AND MASTER SCHEDULES

Location-based scheduling model projects as a series of locations in which activities flow through different units in turn. The flowline method is a location-based scheduling method that graphically represents activities as a single line where the line passes from the lower left corner (start of location, start of duration) to the upper right corner (end of location, end of duration), and represents a crew passing through a location (Kenley & Sepännen, 2010). Moreover, it is possible to represent several crews as a fast way to model production. For the case of work packages at the master-level planning, all crews and activities can be modelled as a single line before splitting into several lines for each crew. Flowlines were used in previous research as a powerful tool for visual management in construction (Brioso et al., 2017). Lehtovaara et al., (2021) presented a client-driven project's operation strategy at the master programme level for collaborative iterations and transparent communication of construction plans. They suggested the following Key Performance Indicators (KPIs): total gross area (m^2), the quantity of work per gross area (e.g., tonnes of rebar per gross area), lead time (how fast the whole production is completed from start to finish), batch-specific lead time (how fast a batch or location is completed from start to finish), and production's tightness (average area occupied by a single worker). The authors argued that clients would drive the operations process by requiring these performance indicators in procurement which in turn would guide contractors in designing the production system accordingly. Thus, flowlines and performance indicators can be integrated to detect waste in the production system and drive performance improvement.

BATCHING

Large batches in the production system lead to an increased amount of simultaneous use of space for several tasks and result in increased lead times whereas smaller batches compress the lead time, but create vulnerability in the production system, especially in projects with high variability (Lehtovaara et al., 2021). Ward & McElwee (2007) argued that mass production is the prevalent modus operandi in the UK construction sector which is contrary to the fundamental principle of lean thinking of continuous workflow. They have shown that the concept of batch reduction or increased number of batches is not fully understood in construction and sites run on large batch areas of whole floors. After collecting data from projects, they simulated the programme savings by reducing batch areas. Maturana et al. (2003) also simulated construction scenarios and showed that the increased frequency of concrete pouring reduces workers' idle times in the structural phase of a multi-storey building. Similarly, Valente et al. (2013) showed that reducing the batch size from an entire floor to an apartment reduces the fit-out phase programme. Thus, there is evidence of potential improvements using the batching technique. However, there is little evidence of how batching drives performance during the structural phase of building projects.

METHOD

Three major residential and commercial projects in London were selected for this study. The scope of data collection and analysis was the superstructure structural frame. A summary of the buildings is presented in Table 1. These projects were considered suitable to examine performance as they depict new buildings managed by Tier 1 contractors, have a mixture of traditional in-situ and off-site construction, and were built under normal conditions (i.e., not extreme weather or stoppages). As-built construction data were collected from a variety of sources, including documents, installation reports, site visits, workshops, interviews, and access to image data such as 360 images and CCTV. Data were triangulated to ensure reliability. For instance, concrete pour installation data was reviewed using CCTV images and delivery data. The "level" was selected as the unit of analysis as opposed to the typical monthly progress measurement found in the three projects. The key independent variables extracted were:

- Gros Internal Area (GIA) in m^2 per level
- Planned & actual start date (installation of the first vertical element on the level)
- **Planned & actual end date (last concrete pour on the level)**
- Number of horizontal concrete pours per level
- Average Batch area per pour (m^2)
- Level of prefabrication (dummy variable 0: Null; 1: High).

Flowlines was selected as the tool to visualise the master-level programme with a location breakdown structure on a level-by-level basis. The rationale for this was the need to present to construction stakeholders, who are mostly familiar with Gantt Charts, a better tool to visualise and understand the actual construction programme and the relationships and interdependencies of timeframes between consecutive levels. The following outcome variables were extracted:

- Production rate: the GIA divided by the planned/actual duration per level
- Start-to-start duration: the duration between the start date of two consecutive levels.

Quantitative methods such as correlation analysis and multiple regression were applied to the data to deduce the relationships and dependencies between the variables.

Table 1: Case studies description (note that A & B are from the same project)

Building	Use	Levels	Structural frame
A	Offices	9	Twin walls, structural steel, in-situ slab concrete pour
B	Offices	9	Twin walls, structural steel, in-situ slab concrete pour
C	Offices	11	Traditional in-situ reinforced concrete
D	Residential	12	Offsite components, in-situ slab concrete pour

RESULTS

The first step in the data analysis was to calculate the planned and actual production rates. Figure 1 presents a plot with the results. Each data point represents a level. All data points above the diagonal show that the actual outperformed the plan whereas all data points below the diagonal indicate that the actual underperformed the plan. It is noteworthy to highlight that the number of data points above the diagonal is far less than the data points under the diagonal. Moreover, the data points above the diagonal hardly exceed the planned performance whereas the data points below the diagonal are far below the expected performance. Thus, these projects show significant performance issues that must be understood to improve productivity.

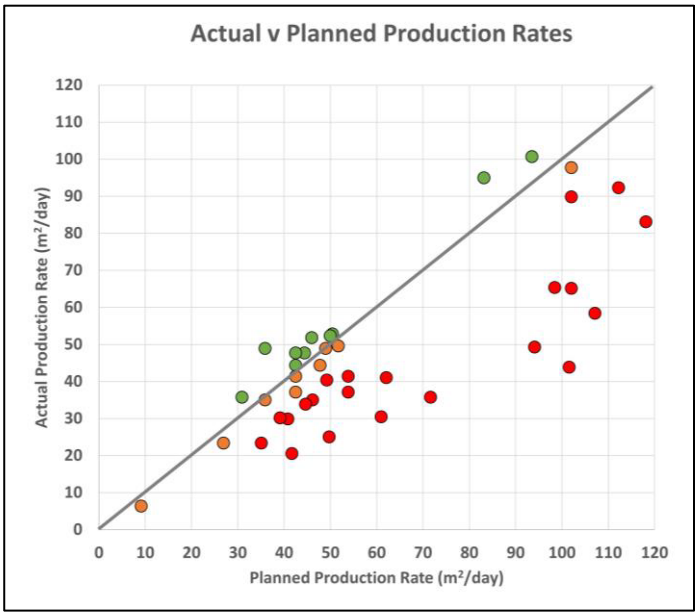

Figure 1: Planned versus actual performance (all buildings)

Table 2 presents the results for production rates, start-to-start durations, number of pours and average batch area for all buildings. Buildings A and B have 1 or 2 pours per level and the biggest batch area (> 600 m^2) which are associated with the highest start-to-start average durations and the lowest overall production rates. The number of concrete pours and batch area are well-known parameters to improve the performance of the production system (Valente et al., 2013; Ward & McElwee, 2007; Alves & Tommelein, 2004). However, these concepts were not fully implemented in the projects under study.

Table 2: Summary of Results

Variables	Unit	A	B	C	D
Production rate (PR)					
Minimum	m^2/day	23	23	21	44
Maximum	m^2/day	49	49	53	101
Median	m^2/day	40	39	32	74
Overall	m^2/day	46	31	59	115
Start-to-start duration (St-to-st)					
Minimum	day	20	20	10	8
Maximum	day	38	28	29	23
Median	day	26	24	14	10
Pours per level (Pours)	-	2	1	3	4
Batch area (Batch)	m^2	619	668	300	357
Prefabrication (0 = No; 1 = High)	-	1	1	0	1

MASTER-LEVEL FLOWLINES

From a master schedule point of view, the aim is to shorten the overall lead time by 1) reducing the start-to-start duration between levels and 2) maximising the level-by-level production rates. Figure 2 presents the master-level actual flowlines of building A and the associated production rates. The highest production rate was achieved in level 7 (49 m^2/day) whereas the lowest production rate was in level 9 (23 m^2/day). The overall production rate of 46 m^2/day is the building's GIA divided by the overall duration. On the other hand, the highest start-to-start duration was between levels 1 and 2 (38 days) whereas the lowest start-to-start duration was between levels 6 & 7 and 7 & 8 (20 days). Moreover, Figure 2 shows an overlap between consecutive levels. This overlap was described by Kenley & Sepännen (2010) as *splitting* which is the result of breaking the work into sections to improve production. Using the metaphor of a *telescope*, the aim is to shorten the telescope by increasing the overlaps between levels. However, Building A had the bigger batches, the longer start-to-start durations and thus, the less overlap or *splitting* between levels.

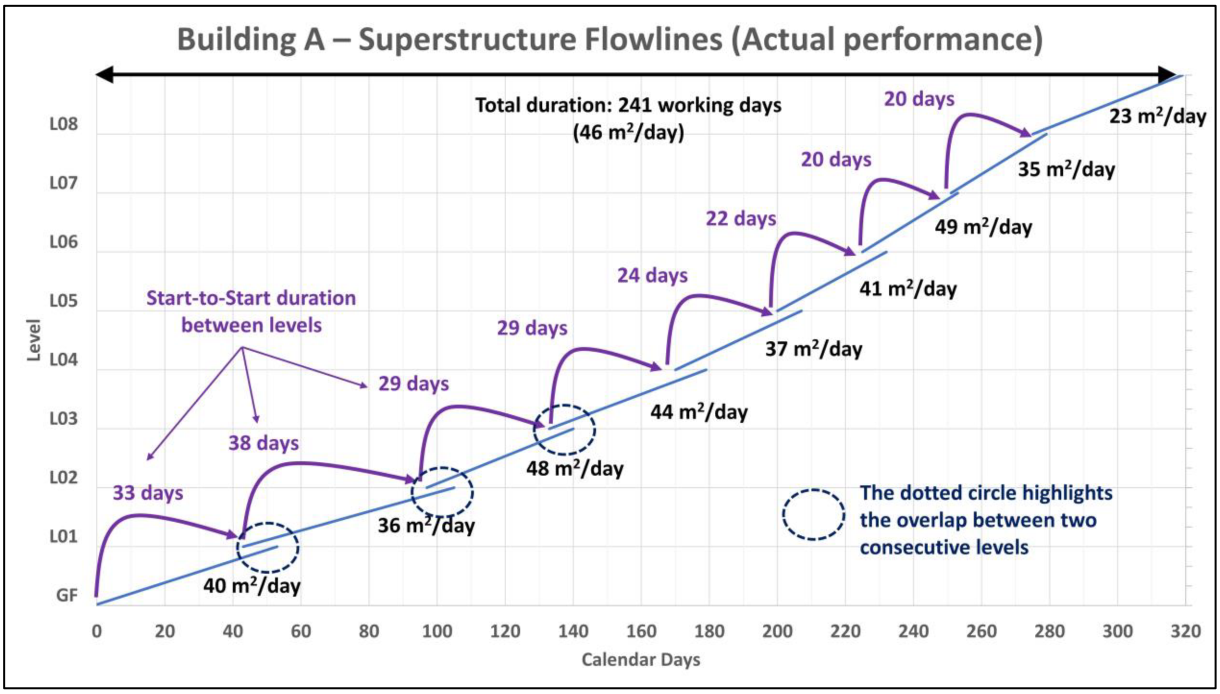

Figure 2: Master-level flowlines for the superstructure of Building A

LOOKING FOR PATTERNS IN THE DATA

Table 3 presents the results of the correlation analysis of the pooled dataset. The results show that 'Production Rate' is significantly correlated to 'Start-to-start duration' ($r=-0.602$, $p<0.01$), 'Number of pours' ($r=0.527$, $p<0.01$), and 'Prefabrication' ($r=0.497$, $p<0.01$). However, there is not a significant correlation between 'Production Rate' and 'Level' or 'Batch area'. Moreover, 'Start-to-start duration' is significantly correlated to 'Number of pours' ($r=-0.537$, $p<0.01$), 'Batch area' ($r=0.700$, $p<0.01$), and 'Level' ($r=-0.436$, $p<0.01$). Nonetheless, there is not a significant correlation between 'Start-to-start duration' and 'Prefabrication'.

To further understand the relationships between these variables, Figure 3 presents the plots of the first dependent variable of interest, production rate, against start-to-start duration, number of pours, batch area, and prefabrication. First, the highest production rate (80 m^2/day and above) is associated with start-to-start duration values between 9 and 12 days. However, these are also associated with production rates below 60 m^2/day. Nonetheless, a start-to-start duration of 20 days and above are *only* associated with production rates below 60 m^2/day. Second, there is an upward trend between the number of pours and the production rate with values above 80 m^2/day with 4 and 5 pours, whilst 3 or fewer pours achieve 60 m^2/day or less. Third, a batch area between 330 and 420 m^2 is associated with the highest production rates. Surprisingly, batch areas under 300 m^2 are associated with lower production rates comparable with a batch area of 500 m^2 or more. However, a closer examination shows that these data points correspond to unusual levels such as level 1, which in most cases were transfer slabs or the top levels which correspond to complex structures in the roof. Thus, the variability of the data does not support any potential relationship between the batch area and the production rate. Finally, projects with the highest levels of prefabrication (dummy variable = 1) are associated with the highest production rates whilst the lowest production rates are associated with projects without off-site components (dummy variable = 0).

Table 3: Correlations between variables (** p<0.01)

	Level	St-to-St	PR	Pours	Batch	Prefab
Level	1.000					
St-to-St	-0.436**	1.000				
PR	-0.146	-0.602**	1.000			
Pours	-0.099	-0.537**	0.527**	1.000		
Batch	-0.434**	0.700**	-0.113	-0.658**	1.000	
Prefab	0.023	-0.032	0.497**	-0.173	0.479**	1.000

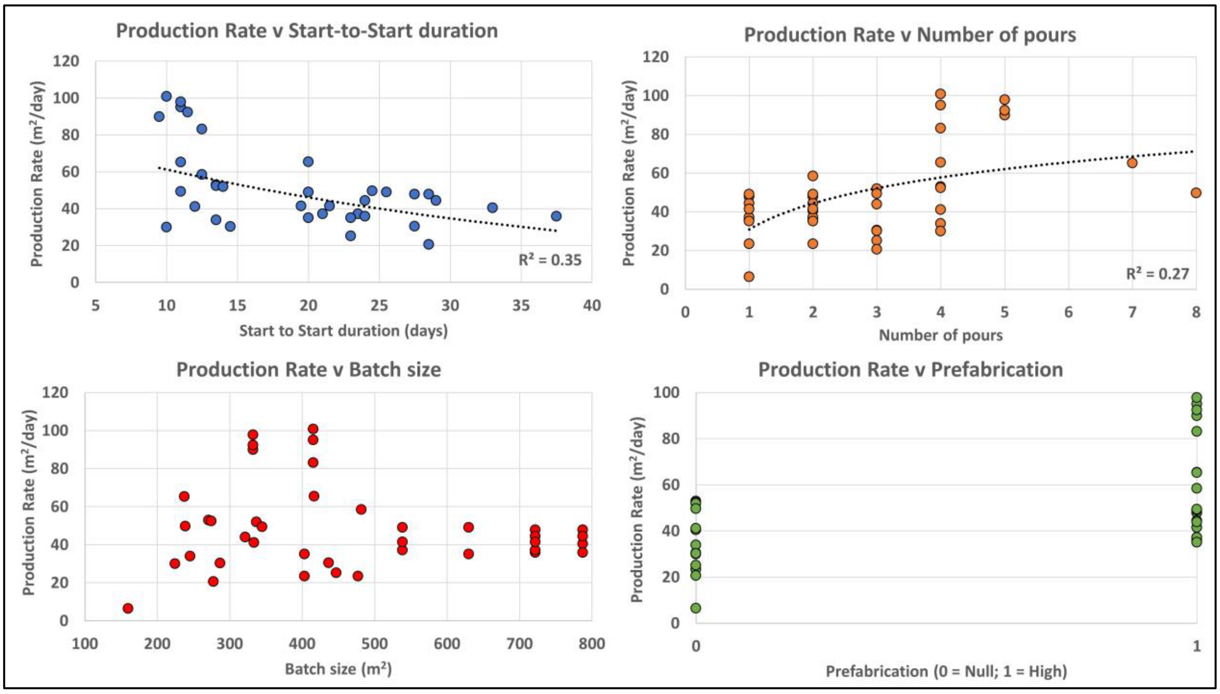

Figure 3: Relationship between production rate and variables under examination

Figure 4 depicts the plots of the second dependent variable of interest, start-to-start duration, number of pours, batch area, prefabrication, and level. First, batch area and start-to-start duration show a high linear correlation. A batch area of 400 m^2 or below is associated with the lowest start-to-start durations. Second, there is a modest relationship between the number of pours and start-to-start duration. For instance, 3 to 5 pours are associated with the lowest start-to-start durations whilst 1 to 2 pours are associated with values of 20 days and above. Third, there is not a clear relationship between prefabrication and start-to-start duration although values of 10 days and above are only achieved in prefabricated projects (dummy variable = 1). Finally, there is a downward linear trend between level and start-to-start duration. Moreover, values between 10 and 15 days happened across all levels. Thus, this is an indication that level is not a predictor of start-to-start duration.

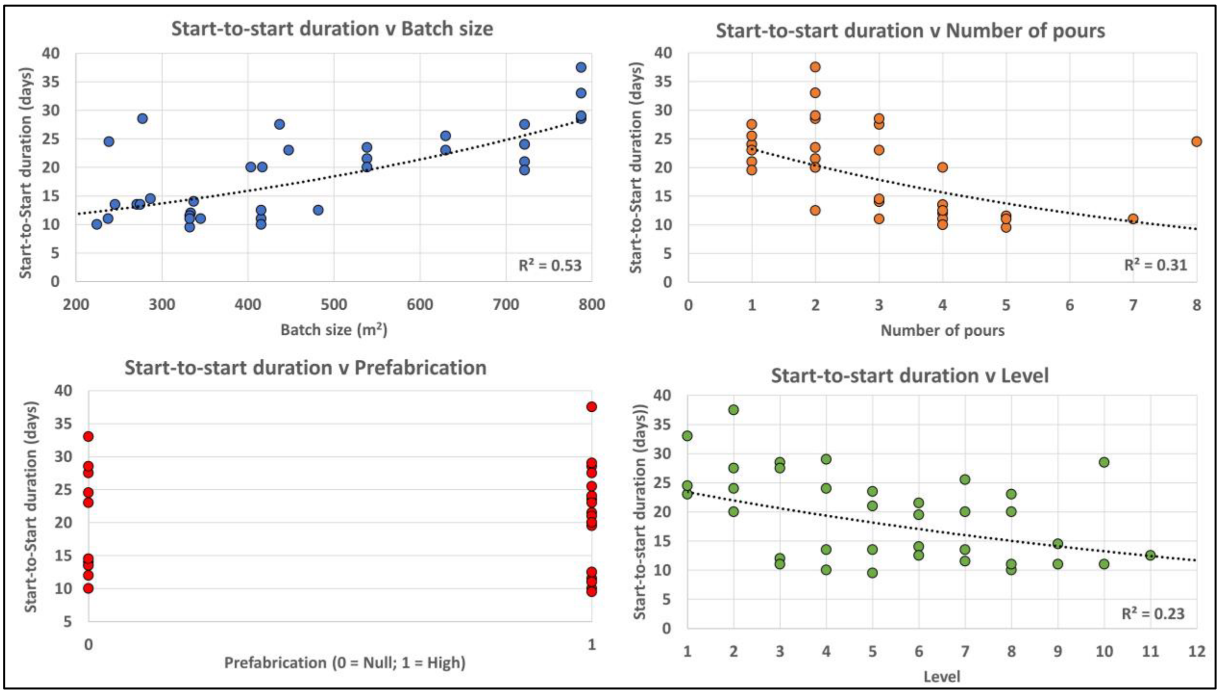

Figure 4: Relationship between start-to-start duration and the variables under examination

MULTIPLE REGRESSION ANALYSIS

A multiple regression analysis was conducted to model the production rate and the start-to-start duration. The results in Table 4 show that start-to-start duration, prefabrication, and the number of pours explain 69% of the variance of production rate whereas batch area was not found to be a significant predictor. These results suggest that all things being equal, every additional start-to-start day reduces the production rate by 0.8 m^2/day. Moreover, projects with a high level of prefabrication perform 26 m^2/day higher than projects without prefabrication. Finally, every additional pour (or batch) per floor increases the production rate by 6.5 m^2/day. Moreover, the results also show that batch area and prefabrication explain 61% of the variance of start-to-start duration whilst the number of pours and level were not found to be significant predictors. These results suggest that all things being equal, every additional 100 m^2 of a batch area increases the start-to-start duration by 3.6 days. Moreover, projects with a high level of prefabrication have 7 start-to-start days shorter compared to projects without prefabrication.

Table 4: Multiple regression results (N=40)

Variable	β	SE	t	p-value
Dependent variable: Production Rate (R^2=0.693)				
Constant	28.633	10.137	2.825	0.008
Start-to-start duration (St-to-St)	-0.832	0.317	-2.622	0.013
Prefabrication (Prefab)	26.220	4.349	6.029	0.000
Number of pours (Pours)	6.485	1.497	4.331	0.000
Dependent variable: Start-to-start duration (R^2=0.606)				
Constant	6.483	2.100	3.086	0.004
Batch area (Batch)	0.036	0.005	7.539	0.000
Prefabrication (Prefab)	-7.148	1.851	-3.861	0.000

These results suggest that at the master level planning, the strategy to increase the production rates is to reduce the start-to-start duration and increase the number of pours per level. In turn, the strategy to reduce the start-to-start duration and increase the number of pours is to reduce the batch area. Moreover, prefabrication has a significant impact on reducing the start-to-start duration and increasing the production rate. In summation, the outcome variables of interest can be explained by the data and planners can consider these relationships during the structural frame's production system design at the master programme level with the use of flowlines.

PERFORMANCE IMPROVEMENT

The next step in the methodology is to use the performance data results to simulate potential optimisation scenarios at the master programme level and assess whether production rates and programme durations can be improved. To do this, building A was selected due to the presentative GIA, the lower number of pours per level, and the lower production rates compared to buildings C and D. Table 5 presents the results of this process. The first step is to increase the number of pours to assess its effect on the production rates and start-to-start durations. For instance, 4 pours of approximately 394 m^2 were selected for levels 1 to 4, whilst 3 pours of approximately 359 m^2 were selected for levels 5 to 7. The estimated start-to-start duration is calculated using the multiple regression results indicated in Table 4 using the batch area (m^2) and prefabrication (0 = null, 1 = high). The estimated start-to-start durations are shown in Table 5 and the actual values achieved onsite are shown in parentheses. Thus, there is a substantial reduction in the start-to-start values which is in line with potential programme reduction. Similarly, the optimised production rate was calculated using the multiple regression results presented in Table 4. The estimated level-by-level production rates are shown in the last column of Table 5 and the actual values achieved onsite are shown in parentheses. Thus, there is a substantial production rate improvement between levels 2 and 8. Finally, the level duration was estimated using the estimated production rate and the GIA. The estimated durations are shown in Table 5 whilst the actual performance is shown in parentheses. For levels 2, 3, and 4, the estimated duration is 23 days which is a substantial improvement from 44, 33, or 36 days.

Table 5: Master programme optimisation results (Building A)

Level	Batch	Batch area	Prefabri cation	Start-to-start duration: Estimated (Real)	Level duration: Estimated (Real)	Production rate: Estimated (Real)
1	4	394	0	21 (33)	42 (39)	37 (40)
2	4	394	1	14 (38)	23 (44)	69 (36)
3	4	394	1	14 (29)	23 (33)	69 (48)
4	4	394	1	14 (29)	23 (36)	69 (44)
5	3	359	1	14 (24)	17 (29)	64 (37)
6	3	359	1	12 (22)	17 (26)	64 (41)
7	3	359	1	12 (20)	17 (22)	64 (49)
8	2	404	1	14 (20)	14 (23)	56 (35)
9	2	404	0	N/A	33 (35)	24 (23)

Finally, Figure 5 presents the overlay of the actual flowlines and the potentially optimised flowlines. The flowlines show that the superstructure programme is shortened from 241 to 146 working days, a reduction of 39%. Similarly, the overall production rate increases from 46 to 76 m^2/day; an improvement of 65%.

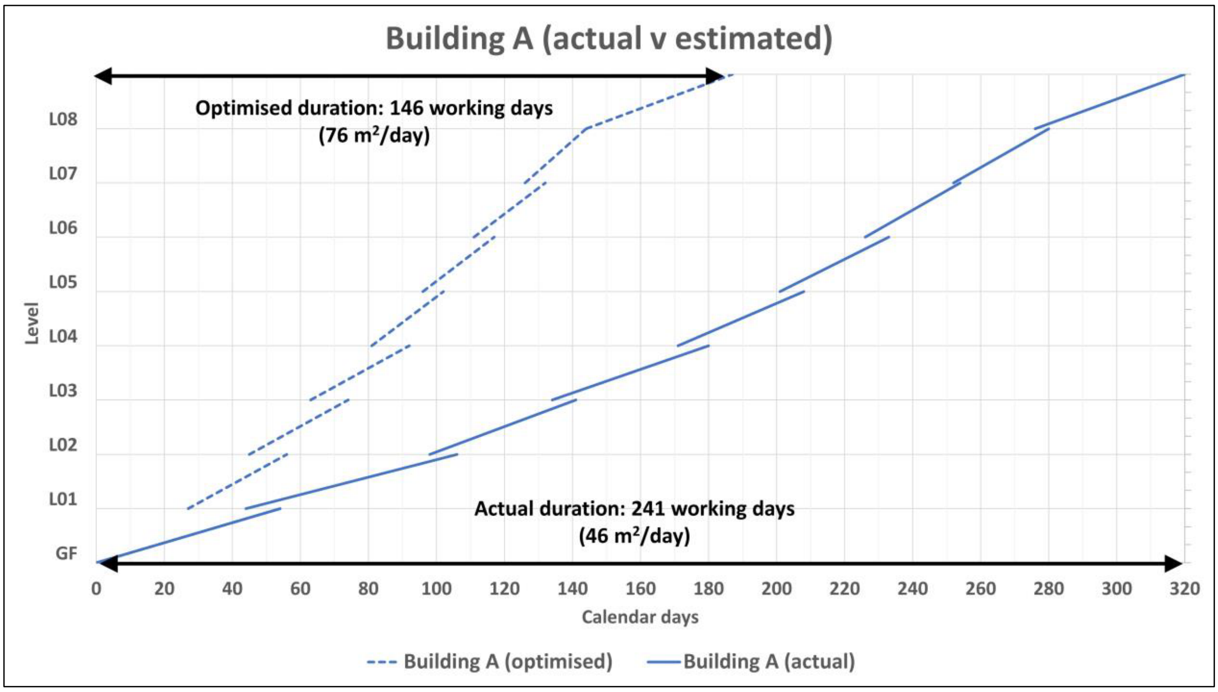

Figure 5: Actual v optimised flowlines for the superstructure (Building A)

DISCUSSION

Data were collected and analysed retrospectively and presented to the industry partners involved in this research. Therefore, the interpretation of the data and the identification of high-level strategic variables is pivotal for understanding what is going on and making decisions. Contractors typically report the SPI (schedule performance index) from the Earn Value Management methodology. This research has shown that additional high-level metrics are needed to compare actual performance, identify the gaps with plans, and look for improvement opportunities. Industry partners who were unfamiliar with flowlines have identified the tool as a powerful means to communicate master programmes, scrutinise the start-to-start durations between consecutive levels, and decide on the best production rates applicable to the project. The use of historical data is fundamental for benchmarking.

First, the data has shown substantial performance issues that were unknown or not fully understood by project stakeholders. The visualisation of master-level flowlines and the level-by-level basis production rate stand in sharp contrast with the weekly or monthly SPI. SPI only shows whether the project is ahead of time or delayed, whereas the production rates are leading indicators that can be timely presented to detect productivity issues. Moreover, the effect of batching on production rates and start-to-start duration becomes clearer. For instance, building D has the shortest average start-to-start duration (10 days) and the highest production rate (115 m^2/day) whereas building A has the longest average start-to-start duration (26 days) and one of the lowest production rates (46 m^2/day). These are associated with the number of batches and the batch area. Furthermore, the iteration of these variables in the early stages of planning can improve the overall slope of the work package's flowline and thus determine the optimum duration. This level of interpretation is certainly difficult to achieve with traditional Gantt charts, as expressed by several project stakeholders.

Second, lean techniques or the Last Planner System (LPS) were not implemented in these projects. However, the concept of batching was tacitly implemented in buildings C and D. Some stakeholders argued that in the UK construction industry, there is a central logic that can be expressed as *"the larger the concrete pour, the better."* This was demonstrated in buildings A and B which had 2 and 1 pours respectively, making it impossible to shorten the start-to-start durations and optimise performance. This logic reflects that planners and supply chain value larger pours to optimise resources on the pour day. This finding was also highlighted in 2007 by Ward & McElwee who argued that the UK construction sector works to large batch sizes to ensure continuity of the same activity for as long as possible. The site logistics of Buildings A and B did not indicate a specific requirement for one or two batches, thus, it was a management decision underpinned by this logic. Moreover, Tier 1 Contractors do not have enough visibility of the construction flows, crew utilisation, and performance issues of their subcontractors. For instance, subcontractors mobilise personnel between projects and send more workers to the site on pour days to meet the contractor's programme. Building D, however, had in-house workers. The contractor maximised labour utilisation by having multi-skilled labourers who can perform several activities to ensure workflow continuity.

Third, more data granularity is needed to understand the differences within projects. The companion paper (Rathnayake et al., 2023) presents data at the activity level and shows that the excess of work-in-progress time had a significant influence on production rates. Moreover, there is an opportunity here to implement the LPS and correlate the PPC metric and reasons for non-completion with master-level production rates. In this research, some performance issues were detected from CCTV cameras and weekly reports. However, these were not captured consistently to ensure a thorough understanding of what went wrong and why. Finally, the variables used in this research are in hands of planners and project managers (i.e., how many batches, batch size, start-to-start duration, and prefabrication). This presents an opportunity to develop a causal model using larger datasets that can inform optimised parameters for new construction programmes. Additionally, this model can be utilised to simulate the performance of new projects, enabling planners the consideration of multiple scenarios for decision-making.

CONCLUSIONS

This research proposes an approach to analyse as-built construction data using master-level flowlines with the aim of optimising project duration. The study collected empirical data from four large buildings located in London. The results of the analysis indicated a significant disparity between planned and actual production rates. To address this issue, master-level flowlines were developed and presented to project stakeholders to improve their understanding of the construction process and ultimately enhance project performance. Two performance metrics were selected to optimise the duration of the work package: start-to-start duration (between levels) and production rates. The results showed a high spread of variability in the performance data within and between projects. However, higher production rates are associated with shorter start-to-start durations, a higher number of slab pours per level, smaller batch areas, and higher prefabrication levels. The results were applied to the building with the lowest performance. Increasing the number of pours from 2 to 4 would reduce the programme by 39% and increase the production rate by 65%. Whilst more performance data is required to build up a robust database, these initial findings can provide contractors and clients with evidence that there is room for improvement. The client was engaged during this research and is willing to prescribe flowlines and performance metrics in future projects. Finally, this work can also be extended to the analysis of the relationships between the superstructure and the next work packages such as cladding and fit-out. The review of the work in progress between work packages, start-to-start durations between levels, and production rates could drive significant performance improvement for the entire project and therefore achieve industry aspirations.

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CAN ADVANCED WORK PACKAGING BECOME A LEAN METHOD?

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ABSTRACT

Advanced Work Packaging (AWP) is rapidly becoming a popular methodology to improve efficiency in construction projects. It is an innovative approach to project management that focuses on the planning, organization, and control of construction tasks on the job site is based on the idea that by organizing work effectively and reducing lead times, it is possible to maximize efficiency and productivity in construction. Nevertheless, Lean Construction (LC) practitioners identified significant shortcomings in AWP such as the lack of attention to buffers while arguing that this methodology is not effective in a practical setting. In this context, this research presents a literature review identifying the criticism of LC practitioners to AWP while identifying similarities and possible synergies where both approaches can complement each other to render better results during the delivery of construction projects. This research identifies the implementation of the Last Planner System® (LPS®) as means to address significant AWP shortcomings identified by LC practitioners while taking advantage of AWP's structured approach to better apply LC concepts. Therefore, the identified synergies and combination of both approaches will contribute to more efficient processes and improvement of construction practices.

KEYWORDS

Advanced work packaging, workface planning, lean construction, integration, collaboration.

INTRODUCTION

Construction projects have the primary objective of meeting construction deadlines, however, we constantly observe cases where this is not met as a result of productivity loss in the industry (Sanni-Anibire et al., 2022). Low productivity has an impact on a country's Gross Domestic Product (GDP), as it accounts for 3% to 8% of its GDP (Hasan et al., 2018). In fact, the construction industry has been struggling to meet increasing productivity demands (Bock, 2015). The Construction Industry Institute (CII) and the Construction Owners Association of Alberta (COAA) proposed AWP as a methodology to increase on-site productivity (Farghaly & Soman, 2021). According to the CII (CII, 2013), AWP methodology is a comprehensive project management approach primarily employed in the construction and engineering industries. Its main objective is to enhance project efficiency, predictability, and productivity. AWP achieves this by effectively planning and organizing work from the project's conception to completion. It involves breaking down projects into manageable work packages and coordinating design, procurement, and construction activities. AWP involves a series of steps

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that are aimed at defining the project's objectives and scope, and at organizing the construction process in a structured and efficient way. These steps typically include planning the construction sequence and identifying the necessary work areas and resources, breaking down the work into manageable units, coordinating the engineering and procurement activities, and preparing the installation and commissioning plans. By following this methodology, project teams can improve their productivity, reduce rework and delays, and enhance the quality and safety of the construction process. These several steps aim to align engineering, procurement, and construction through the creation of specific work packages for each of these activities, which allows for consistent and effective planning throughout the project (Guerra & Leite, 2020).

Koskela (2002) proposed the concept of LC as a new approach to construction, based on the principles of the Toyota production system. LC's main premise is to reduce waste while adding value to the client. Unlike AWP, LC emphasizes a culture that supports workers and continuously improves the production system (Court et al., 2022).

LC provides a range of benefits for construction projects. First, the elimination of waste in construction processes reduces costs and optimizes resource usage. Second, by increasing worker productivity through waste elimination and process improvement, LC leads to greater efficiency and effectiveness in project management. Third, the reduction of delivery times through waste elimination and process optimization decreases indirect costs. Fourth, the continuous improvement of processes in LC leads to a better quality final product, which reduces indirect costs and increases customer satisfaction. Fifth, LC places a strong emphasis on workplace safety, helping to identify risks and reduce workplace accidents. Finally, by promoting collaboration and effective communication among work teams, LC aids in identifying waste and optimizing processes, leading to increased customer satisfaction through cost reduction, quality improvement, and delivery time reduction.

Both LC and AWP differ in terms of their methods and development contexts. However, LC focus on waste reduction and value creation, coupled with its emphasis on a culture that supports workers and continuously improves the production system, makes it a powerful approach for achieving successful and profitable construction projects.; while AWP optimizes the planning and execution of work activities in construction projects to improve project outcomes and deliver projects more efficiently and effectively (Court et al., 2022). Despite these differences, researchers state that AWP and LC have significant similarities between them. Indeed, Mao et al. (2022) argue that AWP has its roots based on LC. An important production system in LC, the LPS® focuses on creating a reliable and predictable workflow between different stakeholders of a project with the last responsible person to perform the work in mind (i.e., the LPS®) (Lean Construction Institute, 2023). As such, AWP can support LPS® by providing the participation of the last planner during planning sessions of work packages(Hood et al., 2021). As a result, the gap between the planning and execution phases can be minimized.

The authors believe that, besides differences between LC and AWP, methods in both approaches can complement each other thus resulting in an improved project development and execution. Therefore, this article aims to discuss the complementarity between LC and AWP, considering their common objectives, differences, and possible synergy between them.

RESEARCH METHOD

The present study is a preliminary exploratory search conducted to identify possible critiques in the application of the AWP methodology. Sources of information related to construction and project management were searched, including indexed journals, technical documents, and conferences. The methodology used is depicted in Figure 1.

Once possible critiques of the AWP methodology were identified, information on LC principles that could be applied to enhance and complement the AWP methodology was sought. The search also focused on similar sources of information.

Overall, the exploratory search aimed to discover relevant and valuable information to address the research question of whether AWP could become a Lean method. The investigation was not conducted exhaustively but focused on discovering new ideas and perspectives that could enrich the discussion.

The methodology utilized in this research involved conducting an exploratory search, which revealed that Workface Planning (WFP) is a crucial component of the AWP approach. WFP is a methodology used for detailed planning and efficient execution of work in the field, which enables early identification of issues and challenges in work execution, allowing for informed decision-making and early risk mitigation. Combining WFP and AWP maximizes efficiency in the construction process, reduces waste, and ensures project quality and safety by providing a structured approach to work management from planning to final delivery.

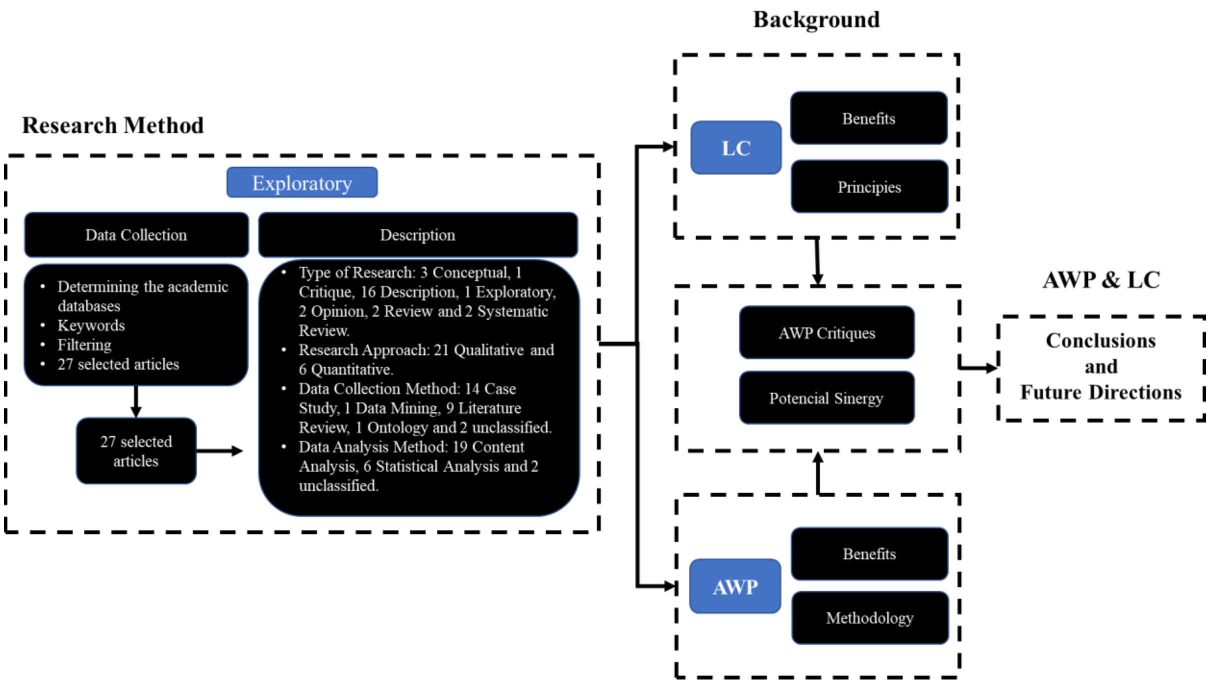

Figure 1: Research method

RESULTS AND DISCUSSION

The research included 25 articles on AWP and its interactions with LC. WFP. Figure 2 shows the volume of publications using these keywords indicating a low number of studies around this topic over the past years.

Through the exploratory search, the researchers found that Workface Planning (WFP) is a critical element of the AWP approach, as it allows for efficient execution and informed decision-making, early risk mitigation, and overall project efficiency, thus providing valuable information that can inform the discussion on whether AWP could become a Lean method. WFP is a fundamental component of the AWP approach, used for detailed planning and efficient execution of work in the field. WFP is a methodology that focuses on managing work packages in the field, allowing work teams to concentrate on effective execution, while AWP is a methodology for managing work across the project, from planning to final delivery. By enabling early identification of issues and challenges in work execution, WFP allows for informed decision-making and early risk mitigation, which contributes to overall project efficiency. When combined, WFP and AWP are tools that maximize efficiency in the construction process and reduce waste, while ensuring project quality and safety. Together, they allow for more efficient and effective management of work in the field, from planning to final delivery.

It is possible that the growing interest in the AWP and WFP methodologies can be attributed to several factors. In 2016, there may have been a greater dissemination of information and experiences regarding the application of AWP and WFP in construction projects, which may have generated interest in the methodology among researchers, professionals, and companies seeking innovative solutions to improve efficiency and quality in project management. Furthermore, the increasing complexity and cost of construction projects may have also contributed to the growing interest in AWP and WFP, as these methodologies can offer a promising approach to addressing these challenges.

In 2022, the interest in the AWP methodology may have been driven by the increasing demand for more efficient and sustainable solutions in the construction sector. The COVID-19 pandemic may have accelerated the need to adopt more advanced practices and methodologies for project management, which may have led to a greater interest in the AWP and WFP methodology. The pandemic has highlighted the importance of flexibility, adaptability, and resilience in project management, which are key principles of the AWP and WFP methodologies. Therefore, it is possible that the growing interest in these methodologies will continue as the construction industry seeks to improve project outcomes in an increasingly complex and uncertain environment.

Year	Publications
1991	1
2010	1
2011	2
2012	1
2013	2
2014	1
2015	2
2016	7
2017	1
2018	1
2019	4
2020	1
2021	4
2022	5

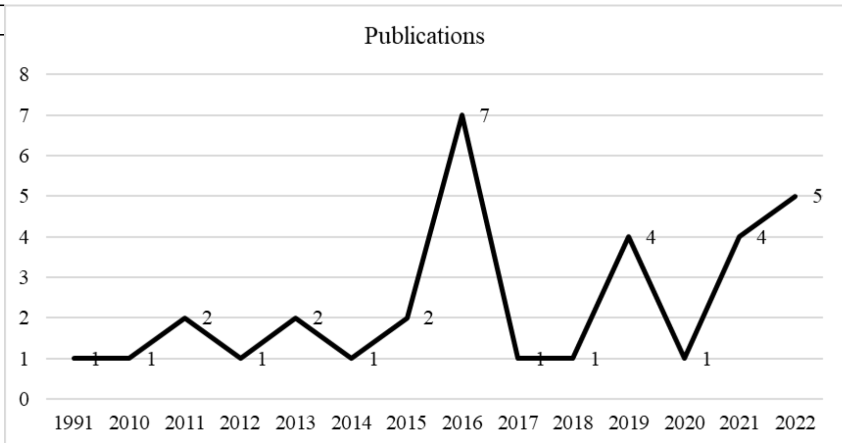

Figure 2: Past publications on AWP by year

BACKGROUND ON AWP

Driven by its recognition in the industry, the CII developed several studies to investigate improvements to the WFP methodology. As a result, CII proposed AWP as an improved version of WFP by providing several case studies and maturity models to identify its benefits (Hamdi, 2013; Ponticelli et al., 2015). The literature identifies benefits in several areas associated with the use of AWP as demonstrated in Table 1. According to Table 1, cost and productivity are commonly improved areas by AWP while benefits in quality and safety are only indicated by half of the authors. Farghaly & Soman (2021) applied AWP on a case study to monitor and control project deliverables in which shorter durations as a result of improved installation sequences onsite. Furthermore, a comparison between traditional projects and other projects under AWP was carried out; in the investigated projects, AWP showed better results in terms of cost, schedule, quality, and safety (Ponticelli et al., 2015). Following the same line, the use of AWP reveals a 25% increase in productivity, a 10% cost decrease, safety improvements, and lesser construction rework compared to traditional projects (Simhadri et al., 2017).

The article by Guerra and Leite (2020), presents a case study on how engineering and construction 3D models can be integrated to support AWP implementation. The article, by

Ponticelli, O'Brien, and Leite (2015), presents case studies demonstrating the benefits of AWP in industrial construction. The article, by Simhadri, Srivastava, and Warren (2017), discusses a case study on how AWP can enhance project control. Finally, the article, by Farghaly and Soman (2021), presents a case study on the development of an ontology to support information management and AWP integration. All four case studies involve the implementation of AWP in various project types, such as petrochemical plants, power plants, gas processing plants, and large-scale oil and gas projects. The case studies highlight the advantages of AWP, including reducing rework, improving communication and collaboration between project stakeholders, increasing productivity, and providing a structured approach to planning and execution.

Table 1: Identified benefits of using AWP.

Benefit	**(Ponticelli et al., 2015)**	**(Simhadri et al., 2017)**	**(Guerra & Leite, 2020)**	**(Farghaly & Soman, 2021)**
Cost	X	X		X
Planning	X	X	X	
Quality	X	X		
Safety	X	X		
Productivity	X	X		X

The use of AWP on a project requires the creation of several work packages. The owner's team is responsible to organize these packages according to the various contracts involved in the project. To do so, AWP establishes a workflow based on early integration in which work packages are defined based on requirements from field personnel. Hence, AWP is a construction-driven approach that adopts the fundamental philosophy of "start with the end in mind". Field personnel will execute these work packages as defined in the first stage. Figure 3 depicts the AWP methodology.

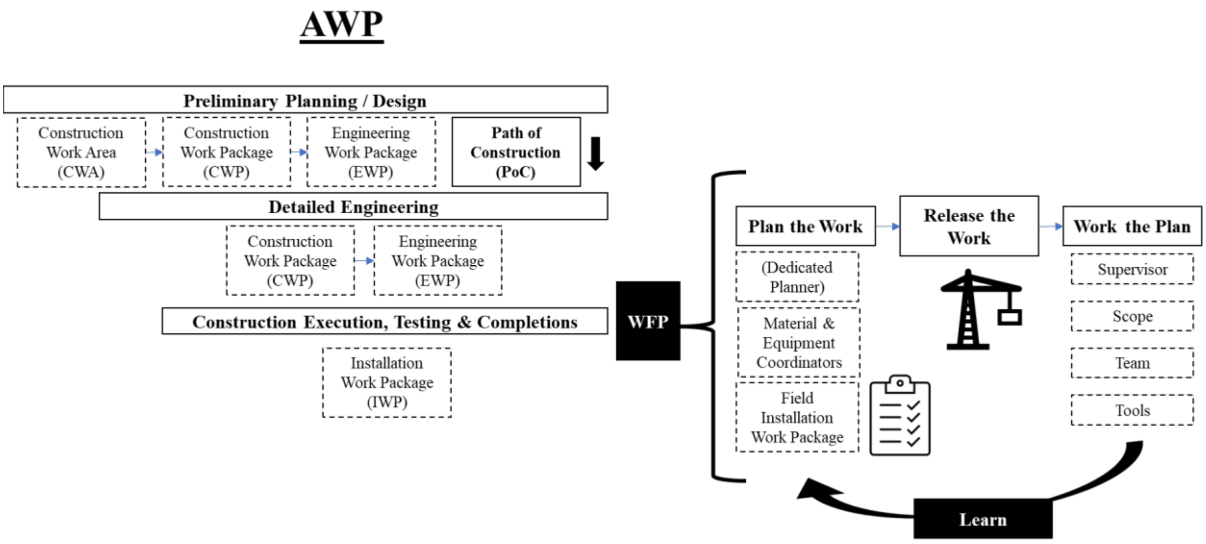

Figure 3: AWP methodology.

As noted in Figure 3, a key requirement in this process is collaboration between construction and engineering during the planning phase to create a constraint-free work environment on the field. This collaboration ensures the project is designed following a sequence that supports construction and its supply chain is organized by breaking down the project scope into work packages (CII, 2020).

AWP IN THE CONTEXT OF LC

The field of application for AWP and LC can be identified by examining relevant literature. According to the CII (CII) (2020), AWP is most used in industrial construction projects, such as those in the energy, chemical, and petrochemical industries. AWP is also applied in projects that require high levels of coordination and collaboration among different stakeholders. On the other hand, Koskela et al. (2002) describe LC as a new theory-based approach to construction, and its main premise is to reduce waste while adding value to the client. LC has been applied in a variety of construction projects, including healthcare, education, commercial, and residential buildings, as well as infrastructure projects. In summary, while AWP is mainly applied in industrial construction and projects requiring high coordination, LC is applied more broadly in a variety of construction projects.

Despite being lauded as an efficient methodology, AWP has gathered critics among the LC community. Ballard and Tommelein (2015) argue AWP is not effective since it focuses its efforts on the creation of work package documentation while not paying attention to production inventories and the creation of a push system as result. Moreover, they recommend the use of discrete event simulation to test the performance of AWP. Moreover, Tommelein (2016) argues that AWP results in large size of work crews, uncertain in schedules, and conflicting transformation processes from systems to product components and locations. Furthermore, Tommelein (2016) claims that supply chains in AWP are not considered as a challenge, which provides an additional complexity to any engineering project. Another critical point is the protection of the production system with a high inventory. As in the previous case, the use of discrete event simulation modelling is proposed to test the performance of AWP. Aligned with this, other studies sharing similar criticism are demonstrated in Table 2.

Table 2: AWP Critiques and Observations

Category	Criticisms/Observations	(Ballard & Tommelein, 2015)	(Tommelein, 2016)	(Fischer, 2021)	(Arbulu, 2019)
Planning	• Focus on document creation and packetization.	X			
	• Lack of synchronization between procurement, equipment, and deliveries.	X	X		X
	• Construction Work Package (CWP) are not made explicit in good form.	X			
	• Forced (Engineering Work Package (EWP) and Purchase Work Package (PWP).			X	
	• Planners are positioned as the ones who will do the thinking for the crews.			X	
Installation Work Package (IWP)	• Installation Work Package (IWP) focused on hours and not on performance.	X	X		
	• Installation Work Package (IWP) decoupled from the constructive logic of a work breakdown structure.			X	
	• Performance protection only protected by high inventory.	X	X	X	X
Production System	• Lack of vision of Balanced Production System.	X	X		X
	• Lack of concepts such as: Buffer, Flux, Push vs Pull, Lead time, and throughput.			X	
Resources	• Underloaded field resources.		X		
Trade Capability	• It is believed that the trade is incapable of effectively planning its own work.			X	

Arbulu (2019) defines AWP as a strategy to place large inventory stocks of materials and information to protect the production system despite not considering the predecessor work-in-process management, capacity, and process variability. Furthermore, Arbulu, (2019) argues that larger buffers generated by AWP will incur to higher project cost despite buffers being estimated by a combination of capacity, time, and inventory. Similarly, Fischer (2021) criticizes AWP pointing out errors in the planning process and the lack of knowledge of construction sequences from planners, which generates disassociation between the AWP packages and the actual work breakdown performed on construction sites due to the logic of construction processes. Indeed, when using AWP, three types of constraints are identified: engineering, supply chain, and site. These are the constraints that must be managed properly to ensure that the construction crew can develop their work as planned (Farghaly & Soman, 2021). Wang et al. (2016) provides a framework for constraint management applicable to both AWP and LPS®. One of the primary objectives in LC is to minimize the inventory and stablish a pull system while developing a culture based on value, mutual trust, and respect to support production. On the other hand, AWP is based on a structured approach (Court et al., 2022). Despite the criticisms presented in this section, the present work identifies potential synergies between LC and AWP as described in the following sections.

POTENTIAL SYNERGY BETWEEN LC AND AWP

Despite the identified differences, AWP and LC share the objective of improving efficiency and quality, constraint management, and stakeholder integration. Court et al. (2022) establishes the main difference between these approaches, Lean is a culture based on values of trust and mutual respect. Indeed, one of LC's main premises is the importance of achieving the project objectives under an environment of collaboration and integration that is enhanced (Alarcón et al., 2013). Table 3 presents a summary of the similarities and differences between AWP and LC.

Table 3: Comparing AWP and LC: Similarities and Differences

Similarities	Differences
Both AWP and LC aim to improve efficiency and quality, constraint management, and stakeholder integration.	LC is based on a culture of trust and mutual respect, while AWP is a methodology focused on work packaging.
Both methodologies focus on early planning, and AWP uses Interactive Planning Sessions while LC employs the Big Room.	LC emphasizes the importance of achieving project objectives in a collaborative and integrated environment.
Constraint management is a key aspect of both AWP and LC, with AWP using Workface Planning and LC using Last Planner System® (LPS®).	AWP focuses on work packaging, while LC focuses on creating a culture of continuous improvement.
The technology applied to implement AWP or LPS® is important for the success of both approaches, with both benefiting from the use of Building Information Modeling (BIM).	LC and AWP differ in their approach to planning and executing work.
Incorporating LC concepts or techniques into the AWP structure can potentially remediate criticisms of AWP and enhance its continuous improvement process.	AWP and LC have different structures and cultural focuses.

The similarities and differences between AWP and LC can be better illustrated through Figure 4. Initially, the focus on early planning is identified in both methodologies. LC considers the Big Room as a key element to meet all the needs of the stakeholders. Big Room seeks to help better coordination of complex engineering projects (Nascimento et al., 2018). Similarly, AWP uses Interactive Planning Sessions to define an integrated plan for project execution from design, construction, commissioning, and delivery to the customer despite no evidence of any specific techniques applied during the session. Hence, LC can contribute to AWP to motivate collaborative work and, consequently, improve how the work is performed while taking advantage from the structured work packages from AWP, when structured work packages are taken in AWP, it provides several benefits. It allows for the optimization of resources, reduces rework, increases productivity, and improves communication and collaboration among the project team. Structured work packages provide a clear understanding of the work to be performed, the required resources, and the expected outcome, facilitating effective planning, scheduling, and execution. Additionally, the structured approach ensures that work is completed in a logical and systematic order, which helps prevent delays and errors. Overall, taking structured work packages in AWP helps to improve project efficiency and effectiveness.

Another similarity between both approaches is the execution phase. In AWP, constraint management is based on WFP. Both the LPS® and AWP are gaining more attention in the recent years because they consider richer information related to project constraints, which infers better quality decisions (Mao et al., 2022).

The technology applied to implement AWP or LPS® is also a fundamental aspect in order to achieve success in either AWP or LPS®. Figure 4 shows the similarities between the technology pertaining to AWP and LC. The work environment in AWP achieves a better development with the incorporation of technologies such as Building Information Modeling (BIM) contributing to an important support to the AWP methodology, as also LC. BIM is defined as a set of methodologies, technologies, and standards that allow designing, constructing, and operating a building or infrastructure collaboratively in a virtual space (Succar et al., 2012). Therefore, BIM offers a reduction of fragmentation in the supply chain and a better platform for construction management (Wu et al., 2021). In terms of linkage with AWP, BIM methodology is presented as an AWP modernization (Tixier et al., 2017). Similarly, the petrochemical industry values the complementarity between AWP and BIM (Guerra & Leite, 2020) as it strengthens the value stream of the project, allows efficient, and aligned engineering. Therefore, the use of BIM methodology is aligned with both AWP and Lean objectives.

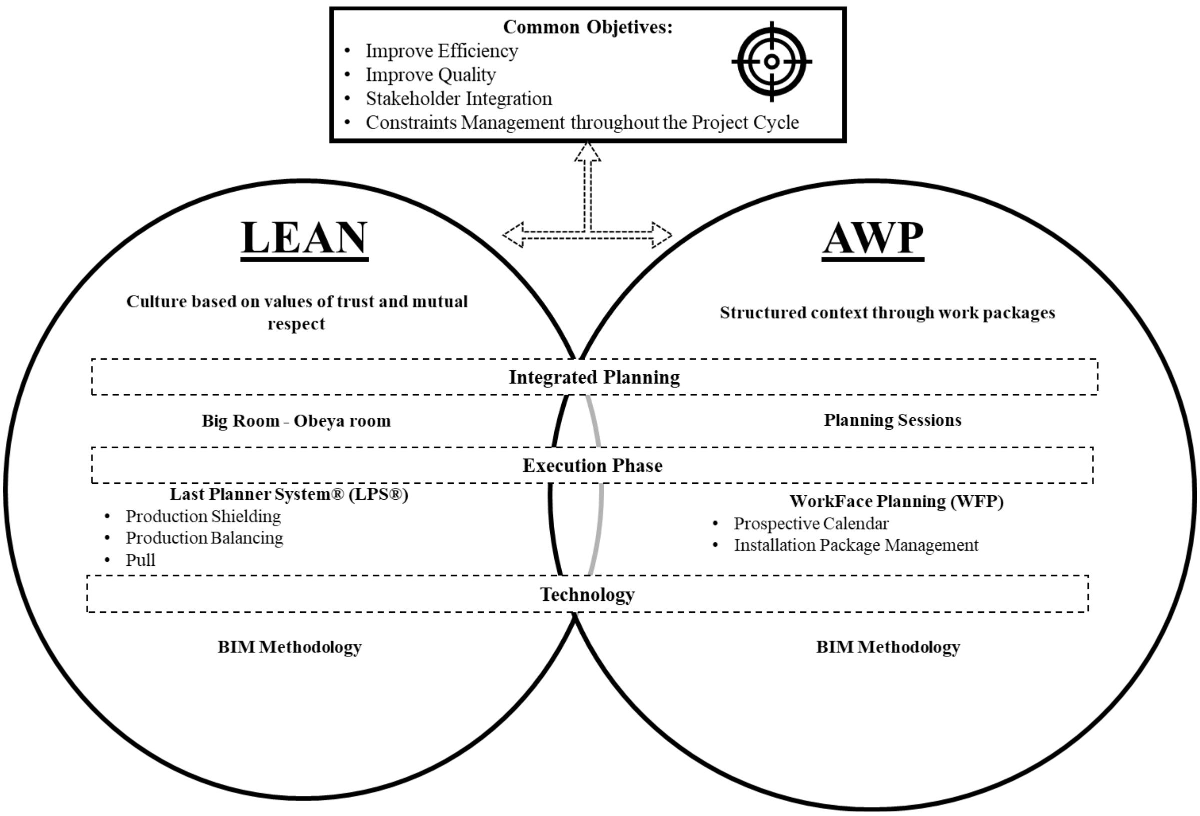

Figure 4: Agreement between Lean and AWP

Finally, aiming to present possible synergies between LC and AWP, Figure 5 shows which elements should be taken from LC and AWP to conform the proposal. The identified synergies rescue the work structure proposed in AWP while considering that each event or decision is supported by LC concepts or techniques. This paper acknowledges the criticisms of AWP which can be remedied by incorporating the DNA of LC in the AWP structure. Both WFP and LPS® are planning systems, seek that the work is executed in a fluid manner, prioritizing a construction rhythm, that allows to benefit the master planning. Figure 5 shows direct feedback to the work planning phase in AWP as in LPS® planning, this feedback process harbours a learning opportunity from the project constraints. In WFP the installation packages are established in a descending way which turns continuously improvement achieved from the information of constraints that is obtained from the field a more challenge and complex process. On the other hand, in LPS® the lessons learned from a project constraint is collected from the field personnel that executed the work and thus facilitating the assimilation of improvements in a continuous manner. As such, AWP can benefit from LPS® by incorporating this approach for continuous improvement in its methodology.

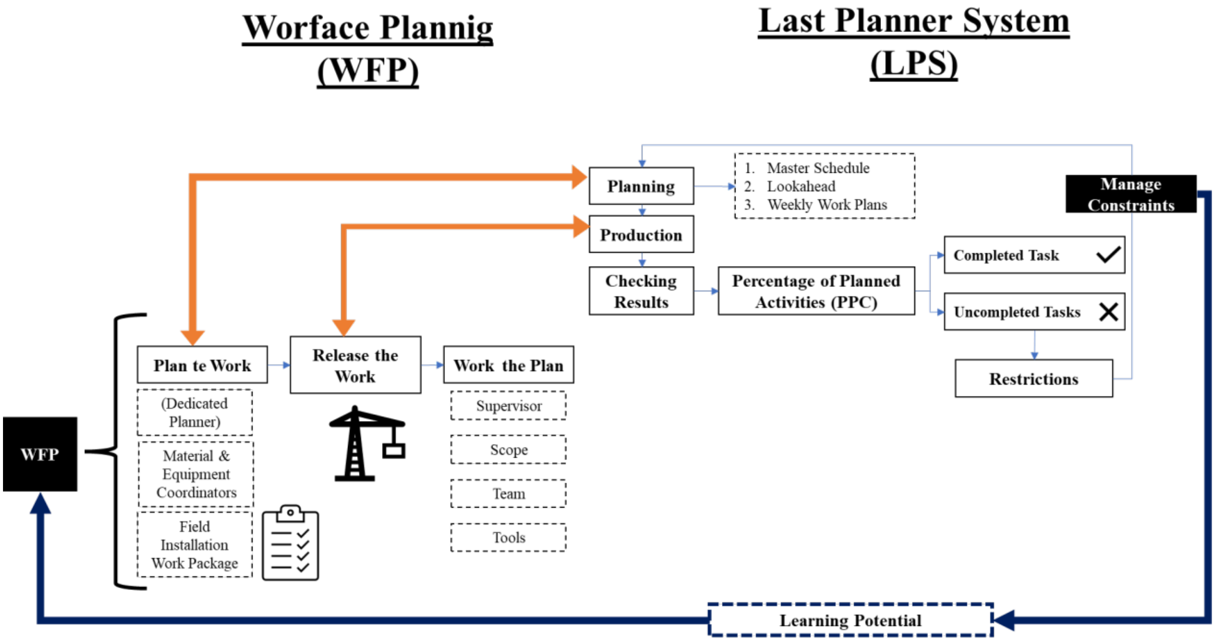

Figure 5: Comparison between Last Planner System® and Worface Planning.

The literature presents some criticism towards the Advanced Work Packaging (AWP) approach, particularly from the perspective of Professor Glenn Ballard and Irisi Tommelein. Despite this, there is evidence of learning opportunities for both Lean Construction (LC) and AWP methodologies. The interaction between these methodologies is worth exploring to identify the possibilities of improving AWP with contributions from LC, while also evaluating the possibilities of implementing the identified synergies. The low volume of publications related to AWP presents an opportunity to carry out academic work and strengthen this approach. For example, Halala and Fayek (2019) propose a framework to assess the costs and benefits of AWP in industrial construction. Additionally, Hood et al. (2021) provide evidence of the linkage between AWP and the LPS®. The incorporation of the identified synergies into AWP will open a field of research possibilities, which complement those already established in the literature.

CONCLUSIONS

Despite studies considering LC and AWP opposite approaches to construction, there is also evidence in the literature of learning opportunities on both ends. Taking this into account, the possibilities of improving AWP with contributions from LC holds a significant potential for its future development while maintaining the possibility to learn from other production planning approaches as well. The low volume of publications related to AWP presents an opportunity to carry out academic work and strengthen this approach. It is necessary to promote case studies that allow quantifying the promised benefits of AWP, as well as evaluating the possibilities of implementing the identified synergies. Before adopting LC concepts into AWP, it is necessary to take into account what factors are modified in the AWP approach when using LC techniques and what is the balance between an AWP and LC methodology. The incorporation of the identified synergies into AWP will open a field of research possibilities, which complement those already established in the literature such as the evaluation of multiple aspects of AWP implementation to quantify both its costs and benefits (Halala & Fayek, 2019).

The potential synergies between AWP and LC can significantly enhance the future development of AWP, as both approaches share similar objectives of improving efficiency and quality, constraint management, and stakeholder integration. LC emphasizes the importance of achieving project objectives under a collaborative and integrated environment, while AWP provides a framework for effective planning and execution of construction projects. By incorporating LC concepts into AWP, such as the balanced production system and synchronized procurement, equipment, and deliveries, AWP can benefit from increased performance and productivity. The bidirectional learning between AWP and Lean could also enable achieving a competitive level for Industrialized Construction, where people, process, technology, and culture are critical factors to consider. Therefore, it is necessary to evaluate the possibilities of implementing the identified synergies and promoting case studies that allow quantifying the promised benefits of AWP.

There is a clear opportunity to evaluate the interaction between LC and AWP methodologies, as there is already evidence on record where the linkage with the LPS® (Hood et al., 2021). A potential avenue for future research involves exploring the application of AWP to other project types. The literature proposes utilizing AWP for modular construction due to the high number of disciplines involved within a limited space. Thus, although AWP is essential, further research is needed to deepen its application in other areas. Furthermore, it is crucial to emphasize that bidirectional learning between AWP and Lean could enable achieving a competitive level for Industrialized Construction by taking into account critical factors such as people, process, technology, and culture.

ACKNOWLEDGMENTS

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HANDOFFS BETWEEN TAKT TRAIN WAGONS: A SYSTEMATIC LITERATURE REVIEW

Mikal Andreassen[1] and Frode Drevland[2]

ABSTRACT

Recent years have seen increased use of takt planning. With takt planning, trades are organized as wagons in a train moving through takt areas in the building. Using takt plans may result in hundreds of handoffs, where finished takt areas are passed on to the subsequent wagons in the train. How these handoffs are carried out can significantly impact a project.

This paper aims to gain an overview of the research literature on takt handoffs in construction projects. The paper identifies and analyses what has been written about handoffs in the takt literature through a structured literature review. The study identified 122 papers on takt in construction. While none of the identified papers dealt directly with handoffs, 22 had some discussion of handoff-related issues.

From the literature, the paper identifies several issues related to takt handoffs and possible solutions – most notably: 1) To ensure successful handoffs, capacity buffers and progress control may help ensure that the takt areas are completed on time. 2) Requirements for what wagons must do before handoff should be clear to avoid problems that can delay the entire train. 3) Contracts that structure payments after handoffs of fully finished areas will incentivize the wagons to finish their takt areas before the handoff. 4) A handoff protocol can be a helpful tool for structuring handoffs.

KEYWORDS

Lean construction, takt planning, handoff

INTRODUCTION

Over the past decade, takt planning has experienced increased attention – both within the lean construction community (Halttula & Seppänen, 2022) and the construction industry as a whole (Lehtovaara et al., 2021). The method has been used in several countries, such as the United States (Frandson et al., 2013), Germany (Haghsheno et al., 2016), Norway (Vatne & Drevland, 2016) and Finland (Lehtovaara, Heinonen, et al., 2020).

The term takt is probably best known in connection with music, where musical works are broken down into beats with a fixed frequency (Haghsheno et al., 2016). This principle has been transferred to the construction industry, where projects are broken down into work packages that can be carried out within a chosen time interval. Several specific approaches exist to manage projects in this way – notably Takt Time Planning (e.g. Frandson et al., 2013) and Takt Planning and Takt Control (e.g. Binninger et al., 2017). Both aim to create continuous project flow by balancing work packages so they can be carried out at a steady frequency – i.e., takt (A.

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Frandson et al., 2013). This paper uses *takt planning* to refer to all takt-based planning approaches.

Building projects involve multiple trades with interconnected tasks that must be completed in a specific order. The workflow is characterized by chains of dependent tasks, which Tommelein et al. (1999) refer to as parades of trades. These occur in several areas of building projects, such as structural, technical and interior work. A parade of trades is similar to an assembly line; however, instead of the product moving through workstations, the workstations move through the product.

Takt-planning typically visualizes parades of trades as trains (Haghsheno et al., 2016). Each wagon in a train has workers, primarily from only one trade, who have fixed work tasks. When organized in the correct order and joined in a train, all tasks are represented by a wagon in the takt train. The fact that the train runs on rails illustrates the dependence between the wagons – no wagons can pass each other. Furthermore, the wagons are typically tightly coupled – i.e., there is no buffer between them. Therefore, if one wagon slows down, so will all the following wagons.

Takt planning divides a project into several parts, called takt areas or zones (Binninger et al., 2017; A. Frandson et al., 2013). The train moves through these takt areas in a specific order, so each wagon is alone in one takt area at a time. Each wagon's time in a takt area is called the takt time. Since the takt time is the same in all takt areas, the size of the areas must be adjusted so that the workload for one wagon is equal in all areas. At the end of each takt time, each wagon must hand off its takt area to the subsequent wagon.

Previous authors have used both *handoff* and *handover* to refer to a wagon completing its work in a takt area and the next wagon taking over the area. However, since the term handover is also used for handing over the final project deliverable to the owner, this paper will use the term handoff to avoid ambiguous terminology. More precisely, we define handoff as the situation where there is an interface between work operations (Lehtovaara et al., 2022), and finished work is handed off from one trade to another for further work (Biotto et al., 2017).

Takt planning has several advantages, but to achieve these, the interface between the train wagons is crucial (Frandson et al., 2015), and the handoff of work is necessary for further work to be carried out (Lehtovaara et al., 2022). In other words, good handoffs are essential to ensure that a takt plan is well executed. The tight coupling between the wagons in the takt train entails that untimely handoffs will cause severe issues for the construction process. In addition, handing off unfinished takt areas also causes issues. For example, handoffs of unfinished takt areas can increase the number of production delays (Dahlberg & Drevland, 2021).

While the literature acknowledges the importance of takt handoffs, no authors have published any works focused on the handoff of takt areas between takt wagons. The past decade has seen published over a hundred papers about takt in construction – encompassing many vital aspects of takt planning – but none dedicated to handoffs. To aid future research in this field, this study identifies and analyses literature on handoffs between takt train wagons in construction through a systematic literature review. This study was carried out as part of a larger Design Science Research based study on ensuring good handoffs when using takt in construction projects.

METHODOLOGY

We conducted a systematic literature review based on the methods described in Snyder (2019). The study relied on two databases to identify literature; Scopus and IGLC.net. Scopus is one of the world's largest databases for peer-reviewed literature and contains literature from the most prominent journals in many disciplines, including construction. Most peer-reviewed literature on takt can be found here – including most papers published through the IGLC. However, Scopus can be a year or two behind the IGLC conferences and what has been published on IGLC.net. Therefore, we conducted a supplemental search in the IGLC.net database.

Figure 1 illustrates the flow for identifying, screening, and including papers. Given that takt is a rather specific term and that the total body of literature on takt in construction is limited, we were able to start with broad search terms. First, in Scopus, we used the search string "TITLE-ABS-KEY (takt AND construction)" to identify all the works in the database related to takt in construction, yielding 106 papers. Then, with the IGLC.net database, we searched for "takt" and found a total of 84 papers; 68 were duplicates of the ones already identified in Scopus, leaving us with 122 papers.

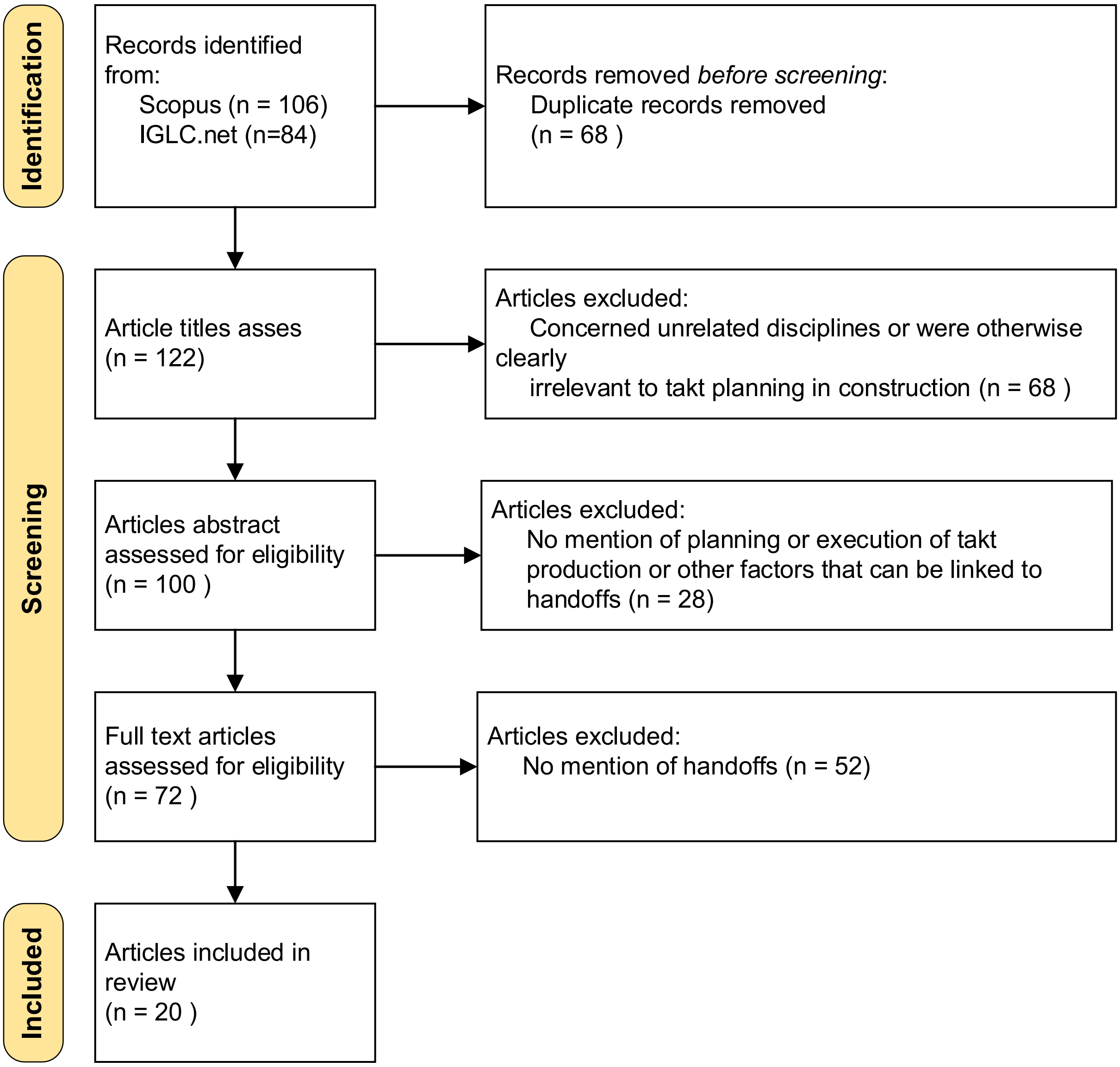

Figure 1: Literature review flowchart (based on Page et al., 2021)

In a systematic literature review, there must be clear selection criteria for the process to be transparent and accountable (Snyder, 2019). We carried out the selection process in three steps. In the first step, we reviewed the titles and excluded 22 papers that concerned unrelated disciplines or were otherwise clearly irrelevant to takt planning in construction. After that, in the second step, we reviewed the abstracts of the 100 remaining papers. Here we excluded papers whose abstracts did not mention planning or execution of takt production or other factors that can be linked to handoffs. In the third and final step, we read the full text of the remaining 72 papers and selected papers to include. Reading the full text was done to ensure we would catch all information related to handoffs. In the end, we found 20 papers that had content related to handoffs in takt.

The review relied on thematic coding analysis – per the guidelines of Robson & McCartan (2016) – to analyze the identified papers, using the computer tool *NVivo* (n.d.) to code the findings. All the selected articles were loaded into NVivo and read carefully. The codes used were created along the way and adapted as the analysis revealed new aspects of handoffs.

RESULTS

This section presents the results of the literature review. We start by making some general observations regarding what exists of literature, who has written it, and how handoff in takt ties in with the Last Planner System. Following that, we review the very limited part of the literature that describes in any detail how handoffs have been carried out in actual projects. Next, we describe several problems related to handoffs described in the literature and their suggested remedies. Thereafter, we cover how takt handoffs can be used for quality assurance purposes. Finally, we summarise the main findings from the literature review in a tabular format.

GENERAL OBSERVATIONS

What literature exists on takt handoffs?

Of the articles identified, none specifically were on handoff between takt wagons. Instead, most considered various aspects related to the planning and execution of takt plans; However, some considered planning methods in building and construction in general.

Who has written about handoffs in takt?

While conducting an extensive bibliographic analysis is outside the scope of this paper, we made some overarching observations regarding who has written anything about takt handoffs. Although there are many different contributors from around the world to the general field of takt, the papers we identified regarding handoffs cluster primarily around three international communities: The American – affiliated with Berkley (Frandson et al., 2013, 2014; Frandson et al., 2015; Frandson & Tommelein, 2016; Linnik et al., 2013; Salem et al., 2018; Tommelein & Emdanat, 2022), the Finnish – affiliated with Aalto University (Keskiniva et al., 2021, 2022; Kujansuu et al., 2020; Lehtovaara et al., 2021, 2022; Lehtovaara, Seppänen, et al., 2020) and the Norwegian affiliated with NTNU (Dahlberg & Drevland, 2021; Gardarsson et al., 2019; Haugen et al., 2020). Interestingly, while the German community behind the Takt Planning and Takt Control approach has been prolific in producing papers on takt, none of their publications directly concerned the handoff of takt areas.

LPS as the foundation of reliable and predictable handoffs

Several authors point to reliable and predictable handoffs as principles derived from the Last Planner® System (LPS) (Haugen et al., 2020; Kalsaas et al., 2014; Lehtovaara et al., 2022; Salem et al., 2018; Tommelein & Emdanat, 2022). In the context of LPS, takt planning will be a method used to stabilize production and make work events more predictable (Kujansuu et al., 2020; Lehtovaara et al., 2021; Linnik et al., 2013).

HOW ARE HANDOFFS CARRIED OUT?

Among the literature, few authors mentioned actual procedures used for handoffs in projects. Kujansuu et al. (2020) investigated a project that used weekly takt. The project contributors were satisfied and thought this fit well with their familiar weekly routines. They could use the last day to complete the takt area and carry out inspections and handoffs. One contractor in (Lehtovaara et al. (2021)'s study also preferred the use of weekly takt starting Mondays with handoffs on Fridays. Apart from these studies, only Haugen et al. (2020) mentioned any procedure used for handoff in real projects. However, the procedure was used to study the implementation of takt plans. To collect data, a handoff protocol was used. To ensure untampered data, the protocol was made jointly between the wagon that finished and the wagon that was to take over a takt area. In the protocol, they had to note – among other things – whether the wagon had tidied the area, whether they had completed the area 100%, whether they had had to do rework in the previous takt areas, and whether they had carried out the work within regular working hours. If the area was tidied and 100% complete, it was called a perfect handoff, and the next wagon should thus be able to work independently of the previous one.

WHY DO PROBLEMS ARISE WITH HANDOFFS?

While the literature contained limited information about how projects concretely carry out handoffs, we found significantly more information about problems related to handoffs. Several prominent issues emerged from the literature review. Lehtovaara et al. (2022) highlight work not completed on time, not fully completed, of poor quality, in an illogical production sequence, or lacking the prerequisites to be completed. Yaw et al. (2020) also point out that multiple handoffs provide more chances of problems with the handoff. The interviewees of Dahlberg and Drevland (2021) voiced that delays in deliveries of materials, equipment and other necessary assumptions are the most common reason why work was not completed on time, thus resulting in takt areas not being handed off. Work not being finished for handoff was a common thread across several articles.

Takt areas not completed in time for handoff

For takt planning to be useful, all train wagons must finish their work before the time set for handoff (Frandson et al., 2015). If a wagon is delayed with its work and does not hand off the takt area on time, this will immediately affect the following wagon (Lehtovaara et al., 2022). Takt planning, therefore, uses capacity buffers to help ensure that takt areas can be handed off on time (Frandson et al., 2015).

A wagon in a takt train should only utilize 70-80% of its available working capacity (Lehtovaara et al., 2021). This way, workload variability can be managed, and delays avoided. In theory, the work should, on average, take less time than the takt time. This extra time is not wasted but can be used. For example, to prepare the takt area for handoff, assist unfinished takt areas, correct previous work, work in buffer areas outside the takt plan, quality assurance, or innovation and work on continuous improvement (Frandson et al., 2015; Lehtovaara et al., 2021, 2022). Lehtovaara et al. (2021) saw a correlation with good production control among the projects that managed to utilize this additional capacity.

The investigations of Kujansuu et al. (2020) indicate that production becomes more stable when efforts are made in the handoffs between the wagons. Lehtovaara et al. (2022) and Frandson et al. (2014) support the claim that clear handoffs in takt provide a more transparent and stable production. To achieve this stability, and ensure that the areas are ready for handoff in time, Lehtovaara et al. (2022) point to the importance of production control – including meetings, measurements and visual aids that will indicate whether the wagons are on schedule or not.

According to Frandson et al. (2015), controlling progress at shorter intervals than the takt time is crucial to determine as early as possible whether the handoffs will occur as planned. In practice, projects can do this through short daily meetings called “daily huddles”, which aim to coordinate the wagons and uncover any problems so that all of them will complete their work on time for handoff (Frandson et al., 2013; Lehtovaara , et al., 2020). With longer takt times, such as weekly takt, some also use weekly meetings for production control (Dahlberg & Drevland, 2021). These meetings should be held halfway through the takt time so that any delays are detected when there is still time to take measures to make the handoff happen on time. If it is impossible to catch up with the delay in the same week, the project can use a more invasive measure; to stop the takt train. Doing so prevents unfinished takt areas from being handed off; however, it also delays the train's later wagons by the same time the train remains stopped. This delay will not be possible to catch up without making significant changes to the timetable.

Dahlberg and Drevland (2021) found that wagons handing off unfinished takt areas can lead to even more delays later in the takt train. The reason for this is the irrational way wagons must work to circumvent the unfinished previous work, and the lack of sound conditions to carry out their work. It also results in wagons having to return to previously completed areas to correct the non-completed work. All of this can contribute to what they call a parade of delays. Salem et al. (2018) saw a similar effect. They observed that work that was not 100% finished but handed off to the next wagon created costly additional work. The shortcomings could be anything from the workspace not being cleaned to leaving larger tasks behind. According to Linnik et al. (2013), the work in a takt area is only complete when it is ready for handoff for the next wagon. Therefore, it needs to be clear what it takes for a takt area to be considered complete.

Different perceptions of what finished takt areas mean

According to Salem et al. (2018), some people consider their work "done" when they have done enough to allow them to continue in the next workspace. In other words, this does not include the work a wagon must do for subsequent wagons to work unhindered. Furthermore, it does not include tidying up or other work they must complete before they wholly finish an area. This thinking illustrates the difference between being "done" and "done-done."

Salem et al. (2018) found several causes of not being "done-done". In one of the case projects they refer to, no individuals were held responsible for post-work clean-up, and there were no processes to ensure that the areas were tidied after the work was completed. Frandson et al. (2013) point out that the handoff of takt areas actually provides such an opportunity to ensure that the previous work is completed.

According to Bølviken et al. (2015), handoffs must confirm that the work in a takt area has been completed and is of the right quality. Salem et al. (2018) argue that the quality of the work handed off must meet the standards of both the wagon that carried it out and the following wagons. A handoff is an interface between wagons – a lousy finish of one wagon's work will give a bad start for the next. The challenge is that the earlier wagons have few incentives to facilitate the later ones, as there are usually different people who perform the tasks.

Another finding made by Salem et al. (2018) was that there was a lack of a clearly defined standard for what was a finished area. In interviews conducted by Lehtovaara et al. (2021), it emerged that it should be clear which tasks, inspections, and tidying wagons must do before handing off an area to the next wagon. In their research, Haugen et al. (2020) used two requirements for handing off takt areas. These requirements were no more detailed than 1) specifying that the areas should be tidied and 2) the work should be 100% finished. Salem et al. (2018) provide several examples of work that must be completed to be "done-done": Tools, equipment, materials and temporary structures must be cleared away, defects must be corrected, and the area must be tidied. Linnik et al. (2013) argue that the takt plan should specify all the activities that must be done before the handoff.

Lack of incentive to finish

Keskiniva et al. (2022) investigated how contracts between main contractors and subcontractors could be adapted to takt production. One finding was that the subcontractors were incentivized not to finish in the takt areas before handoff because of how their work was compensated. Salem et al. (2018) support this finding, arguing that the traditional way of paying the subcontractors does not consider that the work will be handed off.

Traditionally, renumerating subcontractors have been based on measurements of the amount of work performed (Salem et al., 2018). There are several ways to measure the amount of work done, but no matter which one is used, the subcontractors will make an extra effort to improve the metrics on which they are measured. Doing so comes at the expense of what is not measured – for example, quality or whether the area handed off is 100% finished. According to Keskiniva et al.(2022), such measurement and compensation schemes encourage subcontractors to leave small tasks unfinished in the work areas rather than finishing up in full before moving on

An alternative approach is to divide payments based on milestones, as proposed by Keskiniva et al. (2022). Under this method, subcontractors receive a percentage of the contract amount upon reaching predetermined milestones, encouraging them to complete work quickly and providing easy progress monitoring. Frandson et al. (2013) highlight the benefit of takt planning in measuring progress in smaller and more precise segments, and Keskiniva et al. (2022) recommend linking payments to completed work packages corresponding to takt areas to incentivize and motivate subcontractors to finish their work on time.

More handoffs lead to more problems

Yaw et al. (2020) proposed minimizing the number of handoffs as a strategy to improve handoffs – based on the reasoning that fewer handoffs lead to less time spent waiting and transferring work areas. Supporting this, in a study of six projects, Lehtovaara et al. (2021) found that the takt plans implemented with smaller batch sizes, and thus more handoffs, required more follow-up and effort from managers. They mention the organization of handoffs as a notable reason for the increased need for management. This notion could be related to the observation that small batch sizes gave less time to carry out the takt area handoffs.

Small batch sizes in takt planning have advantages such as shorter construction time (Lehtovaara et al., 2021) and lower cycle time for control of progress (Dahlberg & Drevland, 2021; Frandson et al., 2013). Yaw et al. (2020) argue that a conflict arises between the desire for smaller batch sizes and the benefits of reducing the number of handoffs. Furthermore, they say that the large number of handoffs in construction projects is due to tradespeople being so specialized that they can perform only certain tasks. A recommendation for reducing the number of handoffs is thus to make use of interdisciplinary work teams so that all trades can finish in the work areas without having to visit them several times.

HANDOFFS AS A QUALITY ASSURANCE TOOL

Several authors point out that if the handoff of takt areas is carried out in a good way, then this provides an excellent opportunity to regularly quality assure the work that has been done (Frandson et al., 2013; Haugen et al., 2020; Kalsaas et al., 2014; Lehtovaara et al., 2021; Tommelein & Emdanat, 2022). In the same way that the numerous and regular handoffs in takt planning provide immediate feedback on progress, projects can also use handoffs for quality assurance (Frandson et al., 2013). Lehhtovaara et al. (2020) point out that errors can be corrected immediately among the advantages of using handoffs for quality assurance. The need to return to previous takt areas for rework – disrupting the work of others – disappears. Instant feedback about errors also makes those who cause an error aware of it. Thus, they avoid making the same mistake several times. Over time, they make fewer errors, yielding improved quality. Quality assurance in the handoffs can thus prevent subsequent cars from continuing to work in areas with errors (Tommelein & Emdanat, 2022).

SUMMARY OF FINDINGS

Table summarises the main findings presented and discussed previously in the results.

Table 1: Summary of findings

Findings	Source
Handoffs provide an opportunity to regularly verify progress and ensure quality	Bølviken et al. (2015), Frandson et al. (2013), Haugen et al. (2020), Kalsaas et al. (2014), Lehtovaara et al. (2020), Lehtovaara et al. (2021), Tommelein & Emdanat (2022)
Activities and completion criteria for wagons should be planned and clearly defined	Frandson & Tommelein (2016), Lehtovaara et al. (2021), Linnik et al. (2013), Salem et al. (2018)
Better handoffs contribute to stabilize production	Frandson et al. (2014), Kujansuu et al. (2020), Lehtovaara et al. (2022)
A Monday-to-Friday weekly takt with handoffs on Fridays aligns with workers' familiar weekly routines	Gardarsson et al. (2019), Lehtovaara et al. (2021)
The use of a handoff protocol can facilitate the process of handoffs	Haugen et al. (2020)
Problems with handoffs include work not completed on time, not fully completed, of poor quality, in an illogical production sequence, or lacking the prerequisites to be completed	Dahlberg & Drevland (2021), Lehtovaara et al. (2022)
Handoffs of unfinished work lead to more delays and costly additional work	Dahlberg & Drevland (2021), Salem et al. (2018)
Capacity buffers are utilized to ensure that work is completed on time for handoff	Frandson et al. (2015), Lehtovaara et al. (2021), Lehtovaara et al. (2022)
Production control monitor progress in intervals shorter than the takt time to ensure timely handoffs	Dahlberg & Drevland (2021), Frandson et al. (2013), Frandson et al. (2015), Keskiniva et al. (2022), Lehtovaara et al. (2020), Lehtovaara et al. (2022)
Payment of subcontractors should be linked to takt areas to incentivize the completion of work	Frandson et al. (2013), Keskiniva et al. (2022), Salem et al. (2018)
Smaller batch sizes have advantages, but also increase the number of handoffs, which increase the likelihood of problems occurring	Dahlberg & Drevland (2021), Frandson et al. (2013), Lehtovaara et al. (2021), Yaw et al. (2020)

DISCUSSION AND CONCLUSIONS

The purpose of this paper was to conduct a structured literature review of the literature on the use of takt planning in production to identify what has been written about handoffs between takt wagons. None of the articles identified directly concerned takt handoffs, but several papers had some material concerning handoffs. However, from the analyzed articles, the literature review identified several factors for enabling and supporting good handoffs.

One of the key aspects of ensuring good handoff between the wagons is to ensure that the takt areas are completed in time for the handoff. If a takt area is not completed, it will immediately affect the rest of the takt train. Measures that help ensure that takt areas are completed on time can be using capacity buffers and production control – in the form of meetings that follow up progress.

Setting precise requirements for what should be done before handoff can also help ensure a good handoff. People will have different notions of what lies in the term done and, thus, what they must do before the handoff. The consequences of such a vague understanding of the term can be grave. For example, if a wagon hands off an unfinished takt area, it can affect the conditions that later wagons have for carrying out their tasks, leading to delays. Therefore, what a wagon must do before handoff should be clarified and clearly communicated.

Another finding was that the contracts with the subcontractors might provide incentives not to complete the takt areas. To ensure good handoffs – and that all wagons are entirely done in the takt areas – it may be necessary to adapt contracts specifically to takt production. By basing the payments on the handoff of finished takt areas, contractors will be incentivized to hand off takt areas that are "done-done" – i.e., 100% finished.

The literature review uncovered little regarding actual handoff procedures used in projects. Only one study contained detailed information about how handoffs were handled, employing a handoff protocol. Nevertheless, we would argue that such a handoff protocol can contribute to sound handoff. For example, in a handoff protocol, a takt wagon can record that it has carried out its work as described and that the area is tidy and ready for the next wagon. This way, a structure is created for how handoffs are carried out.

Summarizing the above leads us to four main recommendations for takt handoffs:

- Ensure that takt areas are completed on time through the use of capacity buffers and production control
- Set precise requirements for what should be done by a wagon before handoff
- Use contracts adopted for takt construction
- Consider a handoff protocol to structure the handoff procedure.

Concerning further work, it is evident from the literature review that there is a need to study takt handoffs on construction projects in more detail – how are they carried out, and how can we best enable them? Additionally, it may be worthwhile to investigate the impact of takt handoffs on project performance, such as productivity, quality, and safety. Moreover, future studies could investigate the role of technology in facilitating takt handoffs and improving their effectiveness.

As mentioned in the introduction, this literature review is the first step of a more extensive Design Science Research based study on ensuring good handoffs when using takt in construction projects. Presently, we are investigating the practices of a major Norwegian contractor – aiming to develop better tools and guidelines for them to ensure good handoffs.

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LEAN HEALTH CHECK FRAMEWORK

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ABSTRACT

Lean construction is an approach that prioritizes enhancing quality and value while minimizing waste. Lean management comprises of principles and concepts that must be observed to effectively implement Lean management and leverage its benefits. In line with Lean concepts and principles, appropriate behavior and culture must be properly implemented to achieve successful Lean management, hence necessitating the use of an established health check assessment to evaluate the level of Lean maturity. This study aims to introduce a health check assessment to ascertain the level of maturity of Lean behavior and culture in the construction industry. The health check assessment was formulated by identifying Lean success factors, which were further validated by Lean experts. The methodology employed to achieve the study objectives follows a Design Science Research (DSR) approach, which involves creating a health check framework and evaluating it through an expert panel interview among project parties in a real case study project. In addition to the Lean expert panel interview, other performance metrics, such as percent planned complete (PPC) and constraint information, were collected. The proposed framework was validated, and the results indicate that there may be a correlation between effective team communication and project performance.

KEYWORDS

Lean construction, Lean maturity level, framework, Lean health check.

INTRODUCTION

Planning plays an essential role in construction projects. It tackles uncertainties in a project and improves the efficiency of processes while providing a better understanding of project objectives (Chan et al. 2004). However, the construction industry faces several challenges in conducting reliable planning, scheduling, and budgeting, which leads to additional uncertainties and inefficiencies. To address these challenges, modern project management has been developed over the past forty years (Kerzner, 2017), including Lean project management, which focuses on delivering high-quality products while minimizing waste and maximizing value and quality (Ballard & Howell, 2003). The delivery process of Lean management is characterized with clearer objectives where the product and process can be designed simultaneously, and the production control applies entirely during a project's life cycle (Howell, 1999). This is achieved within an environment of strong communication which is a fundamental aspect of Lean philosophy. Put simply, in the construction context, planning, project management, and communication are closely related and interconnected. Effective planning lays the foundation

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for successful project management, and clear communication is essential for both planning and project management to be successful.

The decision-making process in construction projects is influenced by communication between team members; thus, miscommunication and involved parties' behaviours throughout the process might lead to creating more new tasks (Hamzeh & Aridi, 2013). Put differently, since construction teams are multidisciplinary and temporary, having effective communication to exchange information and collaborate to reach the same goal is crucial. In addition to communication and collaboration, there are some other Lean success factors like transparency, safety, and waste minimization (Bayhan et al., 2019). As can be seen, some critical factors should be considered in Lean implementation to achieve the highest potential. Therefore, this research aims to provide a Lean health check framework to understand the Lean maturity level on a project. The framework consists of first identifying Lean success factors through extensive literature review, which are then validated by an expert panel and used to develop an expert panel interview. The interview is designed and distributed among the participants of a real project and the results are analyzed along with some last planner system (LPS) metrics. Finally, team performance is analyzed, and lessons learned are collected.

LITERATURE REVIEW

THE NEED FOR LEAN CONSTRUCTION

According to PMI's "*A guide to the Project Management Body of Knowledge*," project management is the application of knowledge, skills, tools, and techniques to project activities to meet project requirements. Project planning is essential for controlling project success as it provides the project parties with detailed information about execution dates and resources (Zwikael, 2009). Project management is accomplished through the appropriate application of five process groups, which are: initiating, planning, executing, monitoring and controlling, and closing. Managing a project goes further to include the management of integration, scope, time, cost, quality, human resources, communications, risks, and procurement (PMI 1996; Ballard, 2000).

In the 19th century, Bar and Gantt charts were used for planning and scheduling industrial and construction projects. Afterwards, the Critical Path Method (CPM) was established as a more developed version of the Gantt chart for production management, and it has been widely used since the late 1950's (Henrich & Koskela, 2006). CPM relies on creating construction schedules by breaking the project down into activities and assigning them to task leaders. The traditional project management methods work by delivering project objectives on the activity level through a transformational approach, and while disregarding flow and value generation. Therefore, when activities fall behind their schedule, specific measures must be taken to reduce the cost and duration of delays (Howell, 1999; Diekmann & Thrush, 1986). As a result of shortcomings in traditional project management methods, Ballard and Howell (1998) stated that there is a need to develop a new management system for making sound decisions when it comes to productivity and project progress.

Another reason for introducing a new management system was to reduce variability. A poor management system leads to unexpected conditions and renders objectives unstable and unachievable (Ballard, 2000; Thomas et al., 2002). Unstable conditions are mainly due to variability in performance; so, it is vital to have a new management system that could decrease such variability. Consequently, Lean construction was introduced as a production system that tackles variability and waste. Lean concepts originated in the manufacturing industry. According to Lean manufacturing principles, construction workflow variables are imped system performance (Howell, & Ballard, 1994; Tommelein, 1998).

Lean philosophy began with the Toyota Production System (TPS), and it was developed by Taiichi Ohno. TPS' main concepts include customer value identification, waste reduction by eliminating non-value-adding activities, creating a continuous flow, and seeking continuous improvement (Koskela, 1992; Howell, 1999). Additionally, Lean production focuses on managing a process through achieving value efficiency and providing helpful tools and methodologies for appropriate planning (Faniran et al., 1997).

LPS technique is an essential application of the Lean production system, which helps to control planning, and minimize uncertainties and complexities by involving subcontractors and lower-level management in the planning and control process (Hamzeh et al., 2019; Viana et al., 2017). Moreover, the LPS production planning and control system increases workflow reliability on construction projects (Ballard & Howell, 1998). Several metrics have been developed as part of LPS environment, and among these metrics, Percent Planned Completed (PPC) is the most common. PPC measures the reliability of weekly work planning and tracks the performance of reliable promising. It is calculated by dividing the number of planned activities completed at the end of a short period over the total number of activities promised to be completed at the beginning of that period.

LEAN CONSTRUCTION AND IMPLEMENTATION

Koskela and Ballard (2012) examined that developing new ways of thinking and integrating elements of production management and project management into a comprehensive system for construction is essential for the effective delivery of projects through Lean. Certainly, the transformation towards Lean construction will lead to changes in the culture and its people (Green et al., 2008), at both the temporary organization (project) and the management level (Ballard and Howell, 1998).

According to Hamouda et al. (2014), Lean behaviour is defined as a behaviour that adds or creates value, and this behaviour will impact Lean management. The authors also mentioned that behaviour change is the key factor to improve performance. Implementing sustainable Lean concept is required to change the culture by focusing on Lean behaviour. The authors examined that collecting and documenting the critical success factors of Lean implementation will help to change the culture and create more focus on Lean behaviour.

Bayhan et al. 2019 stated that there should be a clear strategy to implement the Lean culture effectively and enhance its potential. A clear strategy will also help decrease the waste in the system which is one of the main Lean principles. Therefore, the authors introduced a list of enablers and barriers to Lean implementation. In addition, other researchers introduced Lean success factors and barriers (Tayeh et al., 2018; Netland 2016; Salem et al., 2015). Thus, this research aims to implement a Lean health check framework as a clear strategy according to the Lean success factors which have been collected through the literature review and Lean experts' knowledge.

LEAN IMPLEMENTATION SUCCESS FACTORS

Many researchers addressed the critical success factors of Lean construction. For instance, Demirkesen and Bayhan (2020) proposed a success model for implementing Lean philosophy in the construction industry. The model uses Delphi method to administer data collected from a questionnaire conducted with eight experienced civil engineers. It targets identifying seven categories of success criteria and uses an analytical network process to reveal links between the success attributes. The study found that Lean training, availability of Lean tools and techniques, and market share were the most important success factors for Lean implementation.

In another study, Li et al. (2020) proposed a method for assessing the lean construction management performance (LCMP) using the analytic network process-fuzzy comprehensive evaluation (ANP-FCE) model. The LCMP evaluation index system was achieved through literature review and questionnaire surveys. The ANP and Super Decisions software were used to calculate the weights of the indices and the FCE was adopted to carry out a comprehensive evaluation of LCMP. The proposed method can help decision makers identify the strengths and weaknesses of LC management of the evaluated project.

Watfa and Sawalha (2021) identified critical factors necessary for successful implementation of Lean Construction and developed a conceptual framework for adopting it. The authors conducted a literature review and a survey of local construction companies to identify 13 Critical Success Factors (CSFs) categorized into four main constructs: Managerial, Organizational, Structural, and External Factors. The study proposes a preliminary roadmap to guide construction companies in adopting Lean techniques.

Another study by Shaqour (2022) focused on the challenges faced by the construction sector and suggested that the adoption of lean construction approaches can help in reducing waste and enhancing performance. Data was collected from 162 construction professionals, and the study found that the adoption of lean tools positively affects time, cost, quality, safety, environment, and relationships. However, the study also found that while construction professionals apply lean tools in construction sites, their knowledge level of lean concepts is less than the adoption level.

METHODOLOGY

According to Van Aken (2004), scientific disciplines can be classified into formal sciences, explanatory sciences, and design sciences depending on the mode of producing scientific knowledge. In design sciences, knowledge is created through the implementation of a solution that is able to employ or alter a particular occurrence (Vaishnavi and Kuechler, 2007). Therefore, according to Alsehaimi et al. (2012), design science (or constructive research) can assist in developing and implementing innovative managerial tools and tackling different managerial construction problems. Therefore, this approach seems to be appropriate for conducting research in construction management. March and Smith (1995) state that the design science research (DSR) process has two fundamental parts: creating artifacts that can address real-world issues and evaluating their performance in use.

According to Hevner (2007), DSR contains three primary cycles, which are:

1. The relevance cycle: it involves the development of an artifact to resolve a relevant problem identified in a specific environment.
2. The design cycle: it facilitates iterations in the design and assessment of the artifact until a satisfying product is obtained.
3. The rigour cycle: it uses existing past knowledge, skills, and artifacts in the application area to ensure innovation beyond the known.

This research implements the DSR methodology to develop a framework for LPS and social health checks. Three main stages of the research approach are shown in Figure 1, which are: the need for a framework, framework development, and testing of the framework.

Figure 1: Research Methodology Steps

DEVELOPING THE FRAMEWORK

According to the literature review, it was found that there is a need to develop a framework to assess the Lean maturity level of a project. After realizing the need for such a framework, literature review has been conducted to collect the Lean success factors which have been further validated by Lean experts. The collected factors are then used to design questions and create an interview to be run on a real project. The Lean expert panel interview will help to understand the Lean implementation level of the project.

In addition to the interview results, some performance metrics are needed to compare the interview results and Lean project performance. Lean project performance indicators like PPC and constraint information can be used as data-driven decision-making approach to understand the team performance, identify their strengths and weakness, and summarize lessons learned from the project. Since project performance and Lean implementation are time-related, the above-mentioned steps should be done every month to have a clear idea about the strengths and weaknesses. Figure 2 illustrates the health check framework and the steps in detail.

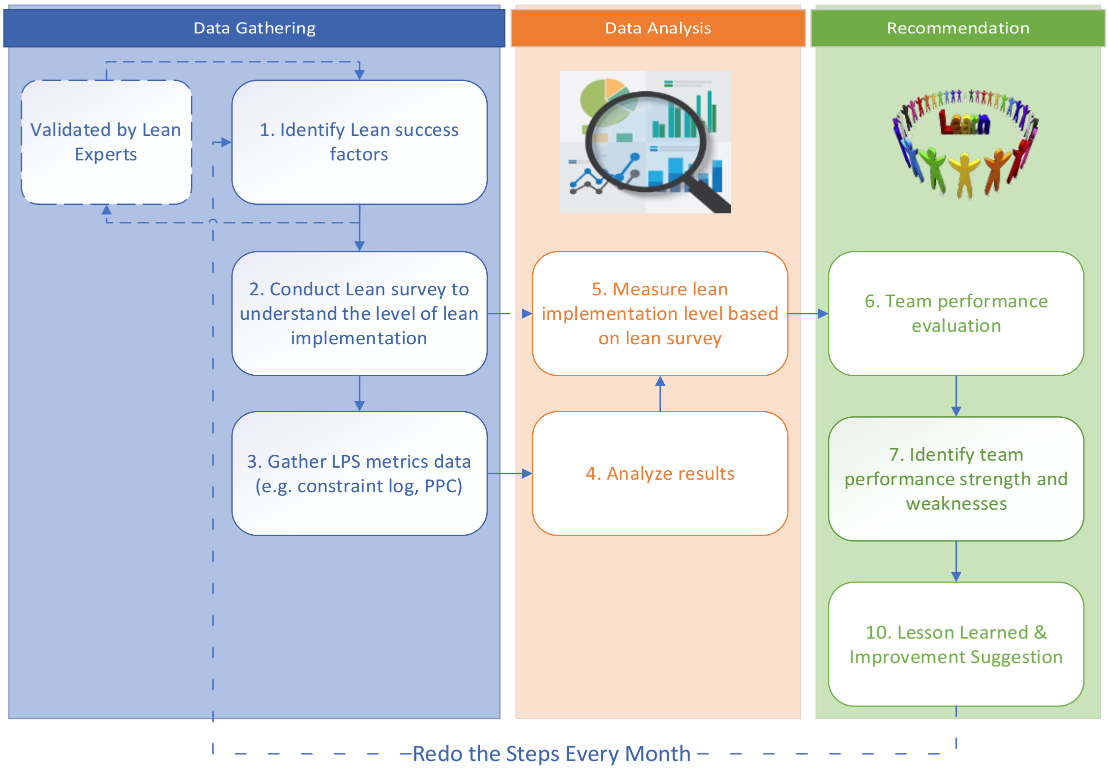

Figure 2: Lean Health Check Framework

DESIGNING THE INTERVIEW

The Lean expert panel interview has been designed to understand the level of Lean implementation in projects based on the Lean success factors collected through literature review (Bayhan et al., 2019; Castillo et al. 2018; Kallassy and Hamzeh 2021; Power et al. 2021; Simmons et al. 2020; Zheng et al. 2020). At first stage, around 90 factors have been collected, which were then reduced based on the research goal pertaining to focusing on the effect of communication on Lean maturity level. The process of reducing the factors and designing the questions has been validated by the Lean experts and finalized as shown in Table 1. After finalizing the factors and questions, the Lean expert panel interview is conducted to understand the Lean implementation level. Table 1 summarizes the factors and questions which have been finalized by Lean experts and project managers and implemented on real projects.

Table 1: Lean Success Factors and Interview Questions

Categories	Interview Questions to Rate Each Factors
Respect for people	"Communication is formalized and communicated when required. "
Teamwork	"The company is flexible in communicating with trades during the execution phase and whenever needed without waiting for RFI." "The company trusts the word given by the trade partners and provides an opportunity to the trade partners for decision making."
Communication & Collaboration	"There is a knowledge-sharing culture in the company." "The company creates the handover structure and schedule of deliverables." "The company cooperates with trades to build trust and commitments
Transparency	"The information on which tasks will be performed during the week is transparent and available to the trades."
Safety	"The company prompts employees about safety in the workplace every day during the daily huddles."
Problem Solving-Learning	"The company is using problem-solving techniques to determine the reasons for variance are identified and discussed during the weekly trades meetings."
Consistency and Standardization	" The company standardizes the best practices and defines certain rules for the trades."
Waste minimization/consciousness	"Handoff quality is good, and no need to rework." Work activities and tasks are planned in such a way to minimize the DOWNTIME."
Innovation	"There is continuous support from the top management."
Continuous improvement–Quality	" The company continually reports the project status and updates the progress." " The company has meetings to discuss lessons learned in the middle of the project." "There is an ongoing effort to teach the Lean concepts and further specialization."
LPS	"The information on which tasks will be performed during the week is transparent and available to all workers of the construction." " The company provides the information regarding what task should be done, when, and by whom. " The company keeps a record of the lessons learned on-site for future projects." "There is a systematic update of the master plan when it is necessary." "Trades are involved in constraint identification and providing solutions."

TABLE TESTING THE FRAMEWORK

The proposed Lean health check framework and dashboard have been tested in one real project as a case study. The case study is a school rehabilitation project in Vancouver, Canada. The project was selected because the Lean management system and the last planner system were used for production planning and control. This case study aims to examine Lean maturity and behaviour and find the gap to improve the weakness. To do so, first, the Lean expert panel interview has been conducted to understand the level of Lean implementation in the project. Second, the performance indicators like PPC and constraint information have been collected from the software that the company was using as their planning software. After collecting all the information, the dashboard has been created to have a current project performance and Lean maturity indicators. The proposed framework suggests that the process should be repetitive every month to understand the process improvement, however, we were able to collect the data to complete the process only one time because of time and data collection limitation.

RESULTS AND DISCUSSION

The interview was conducted on the LimeSurvey platform and was accessible for one month to collect the results. Each respondent was asked to rate the Lean success factors between 1 (low) and 5 (high). After getting all the answers, the average of the results was used to check the Lean maturity level for the project and the result was finalized by designing a radar chart, which can be seen in Figure 3. Figure 3 shows the categories of the success factors with the answers' averages. The interview results in Figure 3 show that communication and collaboration are the lowest and transparency and LPS are the highest among other factors.

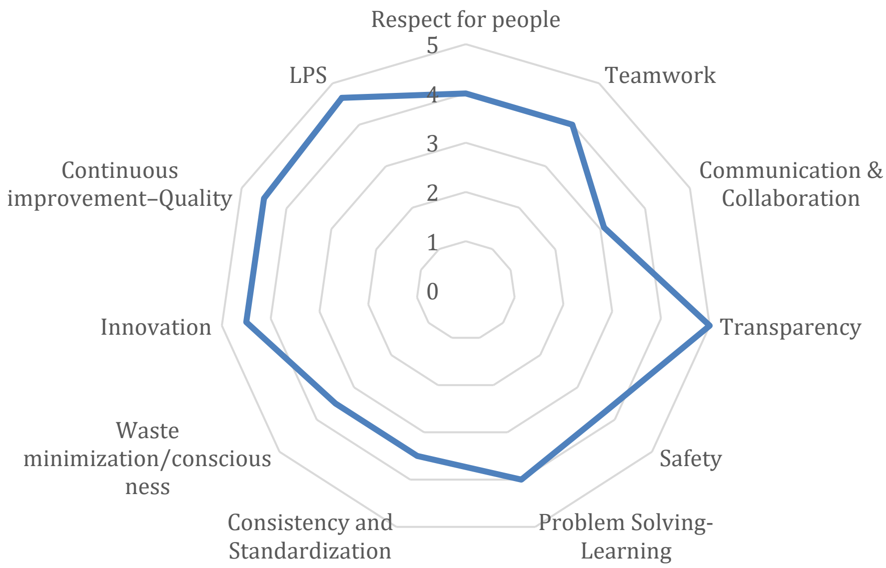

Figure 3: Lean Maturity Level

In addition to interview results, LPS-related metrics like PPC and constraint information were collected from the software used by the company to compare the actual results to parties' opinions. The average PPC was 65% during the study, which is shown in Figure 4. The PPC result shows that the company was struggling to complete the planned tasks and as a result, the PPC rate was not high enough. At the same time, the interview results show that the company has a high LPS implementation rate, and the actual LPS-related metrics show through the questionnaires that there is optimism around LPS implementation.

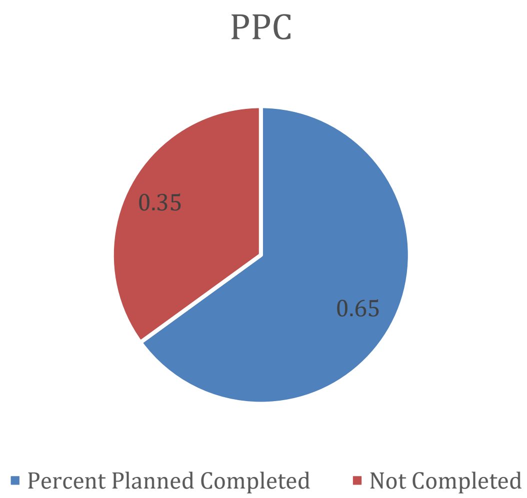

Figure 4: Actual Percent Plan Completed

In addition, the constraint log information has been collected to uncover the reasons for having lower PPC. The constraint information log shows that 135 constraints had to be removed to execute specific tasks, and among the 135 constraints, only 25 were removed on time and 21 were removed ahead of time. During the study period, 40 constraints had not been removed yet, and they were behind in removing 46 constraints. The behind tasks were divided into two sections which are behind by more than 50 days and behind by less than 50 days. The results show that 22 tasks were behind by more than 50 days. Figure 5shows the results in more detail.

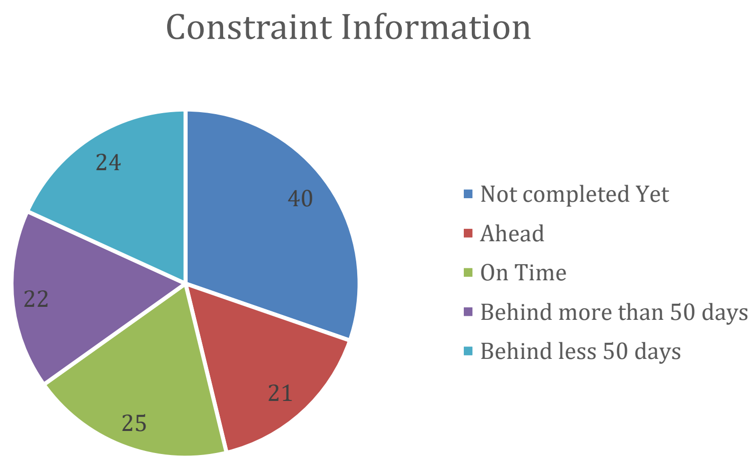

Figure 5: Constraint Log Information

PERFORMANCE DASHBOARD

After collecting all the required information, a dashboard was created to have a clear understanding of the current project's performance. It contains visualized Lean expert panel interview results, actual PPC, goal, and constraint logs. On the top of the dashboard, the user will see the interview results and the middle of the dashboard shows the average and the standard deviation of the interview results which help in visualizing the variability. At the bottom of the dashboard, the user will see all the LPS metrics information that has been collected from the planning software, which can be seen in Figure 6.

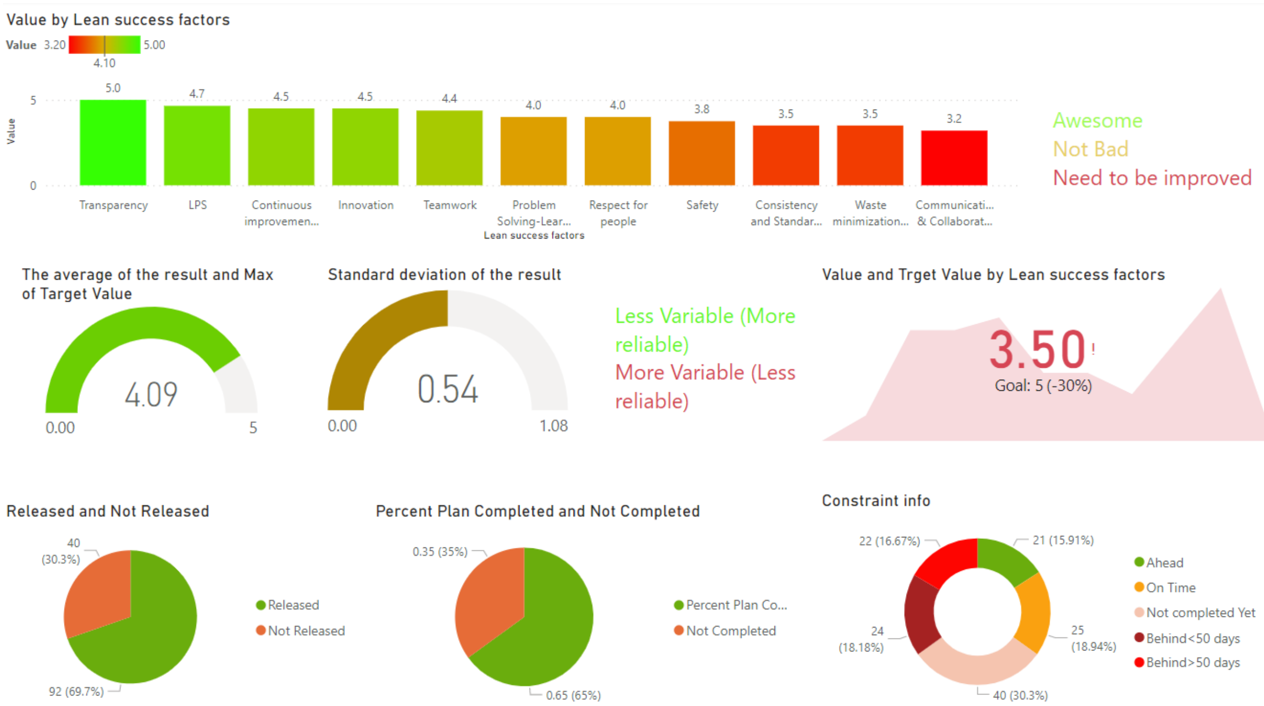

Figure 6: Performance Dashboard

The dashboard for the project adopted as a case study is generated. As can be seen in Figure 6, the interview results show that the company has a high rate of transparency and a low rate of communication and collaboration. In addition to the interview results and LPS-related metrics, the dashboard shows that the company is 30% behind its goal. Therefore, the framework and the dashboard will help reveal the weaknesses and strengths and find room for improvement of Lean implementation.

CONCLUSION

Lean project management is part of modern project management because it focuses on increasing quality and value while decreasing waste. Even though Lean is widely used worldwide, it is still new to many construction professionals, and partial implementation of Lean and LPS will limit its potential. Implementing Lean not only improves production control, but also helps build relationships among construction teams and strengthen social networks; accomplishing an effective Lean environment requires effective communication to collaborate and exchange information. Therefore, increasing the level of communication and collaboration will help individuals and companies implement a more mature Lean system in their projects. Accordingly, this research introduces a Lean health check framework to understand the level of Lean implementation on a project and it also helps to find room for improvements.

The proposed framework has been tested on a real project and the interview results show that the team was optimistic about how they are implementing LPS; however, the data shows that they are struggling with constraint identification and removal, which can directly affect LPS proper implementation (Perez & Ghosh, 2018; Hamzeh et al., 2015; Hamzeh, Zankoul, & Rouhana, 2015; Ballard, 2000). The interview results also show that the level of communication and collaboration is low and needs to be improved. According to Alarcón and Calderón (2003), the communication-transparency factor is one of the main factors that can directly impact PPC results. Thus, more involvement and training would be valuable to increase the Lean maturity level. The authors also noticed that PPC is higher on projects with a collaborative approach. Therefore, by considering the mixed method approach, which is a combination of interview results and data-driven decision-making, there could be a relationship between LPS implementation and the parties' interaction. As a result, there is a need to study such relationship in future research. In addition, some limitations of this study should be addressed in future research such as testing the framework on multiple projects and considering additional factors like project nature and complexity.

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ANALYSING THE IMPACT OF CONSTRUCTION FLOW ON PRODUCTIVITY

Asitha Rathnayake[1], Danny Murguia[2], and Campbell Middleton[3]

ABSTRACT

Construction is one of the least productive industries. A significant reason for this is not viewing the construction process as a combination of flows, i.e. continuous streams of workers, materials or equipment. This paper aims to improve our understanding of construction flow by demonstrating how it can be quantified and how its impacts on productivity can be measured. We discuss two main types of flow: 1) process/location flow, representing the flow of activities performed at a single location and 2) operations/trade flow, representing the activities performed by a single trade through different locations. Based on the literature, we develop a set of metrics for each type of flow. Then, we measure their influence on productivity by using data from four buildings' superstructure work packages. The process flow is compared with the productivity of individual locations, and the operations flow is compared with the productivity of separate crews. The results show that the excess work-in-progress time between successive crews and the mean and variability of production rates for different crews at each location (process flow metrics) can explain 72% of the variation in location productivity. Similarly, the level of work discontinuity (operations flow metric) can explain 52% of the variation in trade productivity. We believe this paper presents convincing evidence of the importance of construction flow in improving productivity.

KEYWORDS

Flow, productivity, work in progress/process (WIP), variability, resource continuity

INTRODUCTION

Productivity, defined as the ratio of output to input, is an indicator of efficiency. The construction industry is globally known for being one of the least productive sectors (Barbosa et al., 2017). This is reflected in the UK's construction industry, which has only shown a 1% improvement in productivity (measured as the gross value added per hour worked) on average from 1997 to 2021. In contrast, the manufacturing sector and the whole economy have improved by 182% and 29%, respectively, in the same period (ONS, 2023). Productivity is a means to an end and not an end in itself. Low productivity indicates low performance in other areas, such as cost overruns, schedule delays and high carbon emissions. Therefore, identifying the underlying reasons for low productivity can help address a number of performance issues affecting the construction industry.

Koskela (1992) argued that traditional managerial methods, such as critical path models, often overlook non-value-adding activities leading to low productivity in construction. The

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author suggested viewing construction as a flow of material and/or information from raw material to the end product. Flow can be defined as a continuous stream of something (Kalsaas & Bølviken, 2010). The lean literature discusses different types of flow, including workflow, worker flow, material flow, equipment flow, trade flow, assembly flow, operations flow, process flow, product flow, information flow and portfolio flow (Tommelein et al., 2022). Some of these flows are incorporated into lean managerial practices.

Despite the efforts of the lean construction community to popularise the concept of flow, a recent survey conducted among construction practitioners from the US, China, Brazil and Finland found that nearly half of the respondents relied only on traditional Critical Path Method-based systems for project management (Olivieri et al., 2019). This shows that the construction industry is yet to fully embrace the concept of flow. There have been efforts to define (Sacks, 2016) and quantify (Sacks et al., 2017) the impact of different types of flow on project performance. However, the impact of flow on project performance has not been adequately measured, highlighting a research gap that needs to be addressed. This paper aims to fill this gap by providing quantitative evidence of how different aspects of construction flow affect performance. We use productivity as an indicator of overall performance.

CONSTRUCTION FLOW

MAIN TYPES OF CONSTRUCTION FLOW

Modern ideas about construction flow derive from the concepts of production flow in manufacturing. More specifically, they can be traced back to the Toyota Production System, which is a system of increasing production efficiency by eliminating waste. It was developed by the Japanese automobile manufacturer Toyota during the mid-20th century (Ohno, 1988). As part of this system, Shingo and Dillon (1989) defined production as a combination of processes and operations. In other words, there are two types of flow in a manufacturing process: 1) process flow which represents the flow of material in time and space, transforming from raw materials to the finished product and 2) operations flow which represents interaction and flow of equipment and operators in time and space, to accomplish the transformation. This distinction is necessary because operation improvements made without considering the process can lead to overall inefficiencies (Shingo & Dillon, 1989).

The concepts of process and operation need to be re-evaluated in the context of construction. Unlike in manufacturing, the construction product is stationary, and the workstations (workers or equipment) move from location to location (Bertelsen et al., 2007). Hence, construction can be introduced as a combination of two types of flow: 1) process/location flow, which represents the flow of activities performed at a single location and 2) operations/trade flow, which represents the activities performed by a single trade through different locations (Sacks, 2016; Tommelein et al., 2022). Simply put, operations flow concerns how individual construction activities can be done faster, whereas process flow concerns how different activities can be sequenced better to improve overall speed. For the rest of the paper, we focus on these two types of flow.

FEATURES OF A GOOD CONSTRUCTION FLOW

According to Koskela (1992), the purpose of visualising construction as a flow is to reduce non-value-adding activities such as moving, waiting and inspecting. In this section, we examine a few concepts that can be used to achieve this, derived mainly from the field of manufacturing.

Optimum Batch Size

In manufacturing, batch size (more specifically, the transfer batch size) is the number of products accumulated at a workstation before being transferred to the next station (Hopp & Spearman). According to Little's law (Hopp & Spearman, 2011; Little & Graves, 2008), as the number of products accumulated at all the workstations in a steady-state production system is gradually increased, two observations are made: 1) the time spent by a product stays constant until a certain point and starts increasing and 2) the rate of output of the entire process increases until the same point and stays constant. If all the workstations produce the same output per unit of time, this optimal point is achieved when the total number of products is equal to the number of machines, i.e. batch size equals one (Hopp & Spearman, 2011).

In construction, having too many products in the process equates to having too many unfinished locations. Following the manufacturing argument, if all the crews in a project generated the same output per unit of time, it would be good to have the number of unfinished locations in the process to be equal to the number of crews, leading to a batch size of one for each crew. However, the steady-state assumption is usually invalid for construction as the production rates of different crews change over time and production durations are limited by project size (Walsh et al., 2007). Hence, more variables are needed to define a good construction flow for real-world conditions. We define a few such variables in the following two subsections.

Less Variability

Variability is the quality of non-uniformity of a class of entities (Hopp & Spearman, 2011). The ideal scenario of a batch size of one introduced in the previous subsection is an average value, as Little’s law deals with averages. Real-world systems almost always have variability (Hopp & Spearman, 2011; Little & Graves, 2008). We can explain the importance of this for construction as follows. In a project, the work done by one crew, e.g. slab formwork, usually feeds another crew, e.g. slab reinforcement. If one crew has high variability, their production rate may be fast one time and slow another time. When they are fast, they will go through the entire location and end up idle until the upstream crew can release the following location. When they are slow, the crew will hold up a location making the downstream crew idle. Both these scenarios lead to a loss of productivity. This is true even when each crew produces the same average output per unit of time, and each crew has a batch size of one. According to the previous subsection, for projects obeying Little’s law, these two conditions should lead to optimum productivity. However, in real projects, variability can have a detrimental effect on productivity.

Hopp & Spearman (2011) discussed two types of variability: 1) variability which occurs at individual workstations and 2) variability which occurs between the transfer of jobs or parts from one station to another. These two correspond to the operations flow and process flow we defined earlier. Variability is quantified as the coefficient of variation, i.e. the ratio of standard deviation to mean, of the operation time (time per location) or arrival rate (locations per unit time). Less variability is an indication of a good construction flow.

Less Excess Work-in-progress Time

In manufacturing, work-in-progress is the total inventory between the start and end of a process (Hopp & Spearman, 2011). Unlike the ideal scenario of a batch size of one introduced earlier, real-world systems may have larger batch sizes (leading to higher work-in-progress) to reduce setup times, as buffers or due to other reasons. Buffers can include inventory, time and capacity allowances to account for the variability discussed earlier (Hopp & Spearman, 2011). In construction, additional or standby resources have to be allocated to address risks. We define excess work-in-progress time as the time corresponding to the additional inventory between two crews that could have been avoided. According to the manufacturing principles introduced above, less excess work-in-progress time is an indication of a good construction flow.

Low Level of Work Discontinuity

Planning for continuous resource use helps maximise productivity and is one of the primary objectives of location-based scheduling (Kenley & Seppänen, 2010). Here, resources include workers and equipment. Perfect continuity is achieved if a particular location starts just after finishing the preceding location with no break. However, in reality, discontinuities occur between successive levels. Besides the apparent loss of productivity due to not working, discontinuous work also increases schedule risk as the crews may not return to work or crew compositions may change (Seppänen & Kankainen, 2004). We identify that resource/work continuity corresponds to a good operations flow.

METHODOLOGY

The aim of this investigation is to identify how construction flow affects the overall productivity of a project and demonstrate how these results can be used to interpret and improve productivity. The research methodology consists of three steps: 1) defining the parameters, 2) collecting project data and 3) analysing the data.

DEFINING THE PARAMETERS

Productivity Metrics

The literature presents various productivity metrics that extend beyond the conventional labour productivity measure. For a thorough and comprehensive summary of these metrics, readers are encouraged to refer to Rathnayake and Middleton (2023). In this study, our focus centres on evaluating the efficiency of the entire crew rather than individual labourers. Hence, we used production rate, i.e. the ratio of output to time, as the indicator of productivity.

Two metrics, overall location production rate and overall trade production rate, are used as the dependent variables of process flow and operations flow metrics, respectively. We define them in Tables 1 and 2. Both metrics use the unit of square metres of floor area per day. For process flow, locations with different floor areas need to be compared. The reciprocal of the production rate is the time taken to complete 1 m^2 of floor area, which is a relative measure. Hence, no adjustment is needed to allow comparison. For operations flow, different activities need to be compared. Using the common output of floor area allows this.

Process Flow Metrics

Table 1 presents the process flow metrics we used in our analysis. They are based on the features of a good construction flow mentioned earlier. All the metrics are scaled to allow comparison among different locations and between projects. Both process and operations flow metrics use floor area instead of time for scaling, as floor area is the constant defining factor of a location or a building, whereas time can vary. Figure 1 visually represents the metrics of a hypothetical project in a flowline chart. A flowline chart is the most common tool to visualise the flow of work through locations. Each activity is represented by a line where the X-axis corresponds to time and the Y-axis corresponds to locations. The process flow advances through time at each location. Blue, green and red lines represent activities 1, 2 and 3 performed by crews 1, 2 and 3, respectively.

The average batch size of a location is calculated as follows (see Figure 1). Consider activity 1 (in blue), which takes nine days to be completed in location 1 ($t_{1,1}$). For the first five days of this period, only location 1 has unfinished work. For the next four days, both locations 1 and 2 have unfinished work. This gives an average of (1*5 + 2*4)/9 = 1.44 unfinished locations during this period. Similarly, the time taken to complete activity 2 at location 1 ($t_{1,2}$) is 16, and the average number of locations with unfinished work during this period is 1.75. $t_{1,3}$ is 1, and the average number of locations with unfinished work is 1. If this is considered a factory, each location corresponds to a product, and each crew corresponds to a workstation. $t_{1,1}$ is the time spent by location 1 being worked on by crew 1. The average number of unfinished locations of crew 1 during that period is the batch size of crew 1 in the process. Similarly, crews 2 and 3 have their own batch sizes. The average batch size of the entire construction process at location 1 is the weighted average of these different batch sizes with respect to time which is then scaled to the floor area, i.e. $((1.44*t_{1,1} + 1.75*t_{1,2} + 1*t_{1,3})/ t_{1,all})/a_1 = ((1.44*9 + 1.75*16 + 1*1)/25)/a_1 = 1.68/a_1$.

The hands-off duration between two consecutive activities is normally defined by the takt-time in the production system design (Frandson et al., 2014). Since the projects under consideration did not formally implement takt-time planning or similar methods, it is difficult to determine the excess work-in-progress times (i.e. durations beyond the takt-time). As an alternative, we assumed that the lowest work-in-progress time maintained by a location with respect to its area is the minimum required time for that building. The rest of the locations are analysed relative to the lowest time (with respect to its area) for the building, i.e. $(w/a)_{min}$.

Table 1: Process/Location Flow Metrics

Metric	Definition	Calculation (See Figure 1)	Unit of Measurement
Average batch size	The ratio of the weighted average batch size of crews at a location to the floor area. Batch size is the average number of unfinished locations worked on by a crew between the start and end dates of a location	Explained above	$1/m^2$
Variability of location production rates	Coefficient of variation of all crew production rates in one location	(Standard deviation of $a_1/t_{1,1}$, $a_1/t_{1,2}$, $a_1/t_{1,3}$)/ (Mean of $a_1/t_{1,1}$, $a_1/t_{1,2}$, $a_1/t_{1,3}$)	Unitless
Excess work-in-progress time	The ratio of the total time between the start of each successive activity and the floor area of a location minus the lowest value for the entire building	$(w_{1,12} + w_{1,23})/a_1 - (w/a)_{min}$	$days/m^2$
Mean location production rate	Mean of all crew production rates in one location	Mean of $a_1/t_{1,1}$, $a_1/t_{1,2}$, $a_1/t_{1,3}$	m^2/day
Overall location production rate (dependent variable)	The ratio of the floor area to the total duration of a location	$a_1/t_{1,all}$	m^2/day

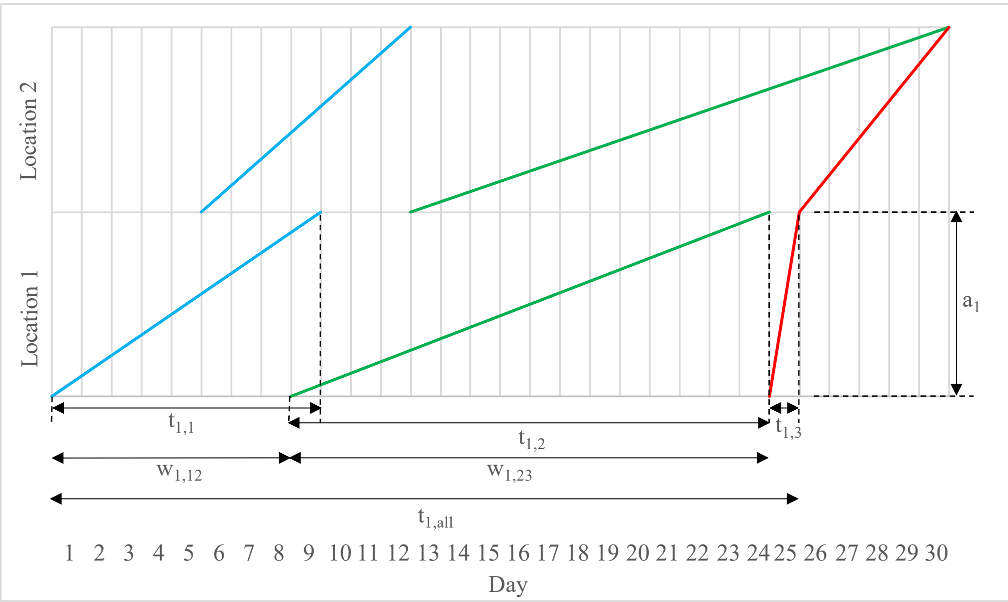

Figure 1: Calculating Process Flow Metrics

a_1 = floor area of location 1
$t_{1,all}$ = time taken to complete location 1
$t_{1,1}$, $t_{1,2}$, $t_{1,3}$ = time taken to complete activities 1, 2 and 3 at location 1
$w_{1,12}$, $w_{1,23}$ = time corresponding to work-in-progress between activities 1, 2 and 2, 3 at location 1

Operations Flow Metrics

Table 2 presents the operations flow metrics we used in our analysis. Figure 2 visually represents the metrics of a hypothetical project in a flowline chart. The four blue lines represent an activity performed by a crew in four locations. The operations flow advances diagonally along flowlines as the trade moves through each location.

Table 2: Operations/Trade Flow Metrics

Metric	Definition	Calculation (See Figure 2)	Unit of Measurement
Level of work discontinuity	The ratio of total time spent by a crew without working in between locations to the total floor area of the building	$(d_{12,1} + d_{23,1} + d_{34,1})/ (a_1 + a_2 + a_3 + a_4)$	days/m^2
Variability of trade production rates	Coefficient of variation of one crew's production rates in all the locations	(Standard deviation of $a_1/t_{1,1}$, $a_2/t_{2,1}$, $a_3/t_{3,1}$, $a_4/t_{4,1}$)/ (Mean of $a_1/t_{1,1}$, $a_2/t_{2,1}$, $a_3/t_{3,1}$, $a_4/t_{4,1}$)	Unitless
Mean trade production rate	Mean of all location production rates by one crew	Mean of $a_1/t_{1,1}$, $a_2/t_{2,1}$, $a_3/t_{3,1}$, $a_4/t_{4,1}$	m^2/day
Overall trade production rate (dependent variable)	The ratio of the total floor area of all the locations to the total duration taken by a crew to complete them	$(a_1 + a_2 + a_3 + a_4)/ t_{all,1}$	m^2/day

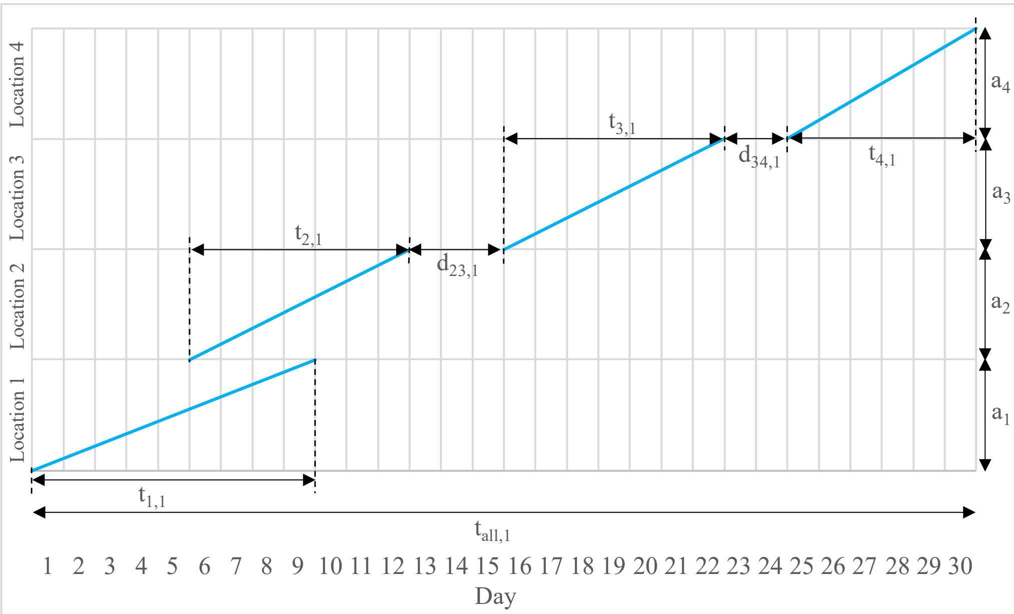

Figure 2: Calculating Operations Flow Metrics

a_1, a_2, a_3, a_4 = floor areas of locations 1, 2, 3 and 4
$t_{all,1}$ = total time between the start and end dates of crew 1 in the four locations
$t_{1,1}$, $t_{2,1}$, $t_{3,1}$, $t_{4,1}$ = time taken to complete locations 1, 2, 3 and 4 by crew 1

$d_{12,1}$, $d_{23,1}$, $d_{34,1}$ = discontinuities between locations 1,2; 2,3 and 3,4 for crew 1

Note that $d_{12,1}$ is 0 because work commenced at location 2 before finishing at location 1.

COLLECTING PROJECT DATA

We used installation and labour data from the superstructure construction of four buildings in London. Buildings A and B are eight-story buildings with steel frames and in situ concrete slabs. Their total gross internal areas are about 10,400 m^2 and 5,700 m^2, respectively. Building C is an eleven-story building with a traditional reinforced concrete structure. Its total gross internal area is about 14,200 m^2. Building D is a fourteen-story building with precast columns and lattice slabs. Its total gross internal area is about 19,000 m^2. A, B and C are commercial buildings, whereas D is residential. The first level of buildings A, B and D were not considered because they used different structural systems with separate activities and crew arrangements. Levels 10 and 11 in Building C and 12-14 in Building D were not included due to data unavailability.

We used three data sources: 1) records of site cameras, 2) installation records by subcontractors and 3) discussions with site personnel. We did not use the master plans updated by planners due to their low accuracy. This is because progress was updated about once a week and had many inconsistencies compared to site camera records and other sources.

ANALYSING THE DATA

Unlike in manufacturing, where a product is a discrete entity, in construction, a location can be defined to have any size. The projects used in this research did not use location-based scheduling. Hence, there were no predefined location breakdown structures. However, each level in a building had a general sequence of slab concrete pours, and the crews usually worked in that sequence. Therefore, a location was defined as the building area corresponding to a major slab pour. Accordingly, process and operations flow metrics were calculated, and IBM SPSS 28 was used to conduct correlation and regression analyses between the variables defined earlier.

RESULTS

There were 86 locations and 19 crews across the four buildings. Figure 3 presents their flowline charts. Buildings A and B belong to the same project, and the subcontractor used a single steel fixer crew for both buildings. The time spent by the crew in the other building is shaded. It corresponds to Portfolio flow as defined in Sacks (2016), which represents the workflow from project to project (in our case, from building to building). The flowlines in Buildings C and D are arranged closer together and seem to have relatively smooth flows with fewer breaks. Conversely, Building B has the worst flow quality, with flowlines spaced apart.

CORRELATION ANALYSIS

Tables 3 and 4 present the results of the linear correlation analysis of process and operations flow metrics. The four flowline charts show that slab concreting usually takes only a day in each location. This is an outlier when analysing process flow metrics. Hence, it was not included in the calculations for the mean and variability of location production rates. Note that adjustments were also made for holidays and weekend working hours.

REGRESSION ANALYSIS

Multiple linear regression of the process flow metrics yields Equation 1 for the overall location production rate. This model has an R^2 value of 0.72. Similarly, the multiple linear regression of the operations flow metrics yields Equation 2 for the overall trade production rate. This model has an R^2 value of 0.52. The variance inflation factor of each independent variable was much less than 5, indicating a low multicollinearity level.

$$\text{Overall Location Production Rate} = $$
$$- 224.96 \text{*Excess WIP time} - 8.41 \text{*Variability of Location Production Rates}$$

+ 0.10*Mean Location Production Rate + 26.15 Equation 1

Overall Trade Production Rate = - 3756.20*Proportion of Breaks + 117.09 Equation 2

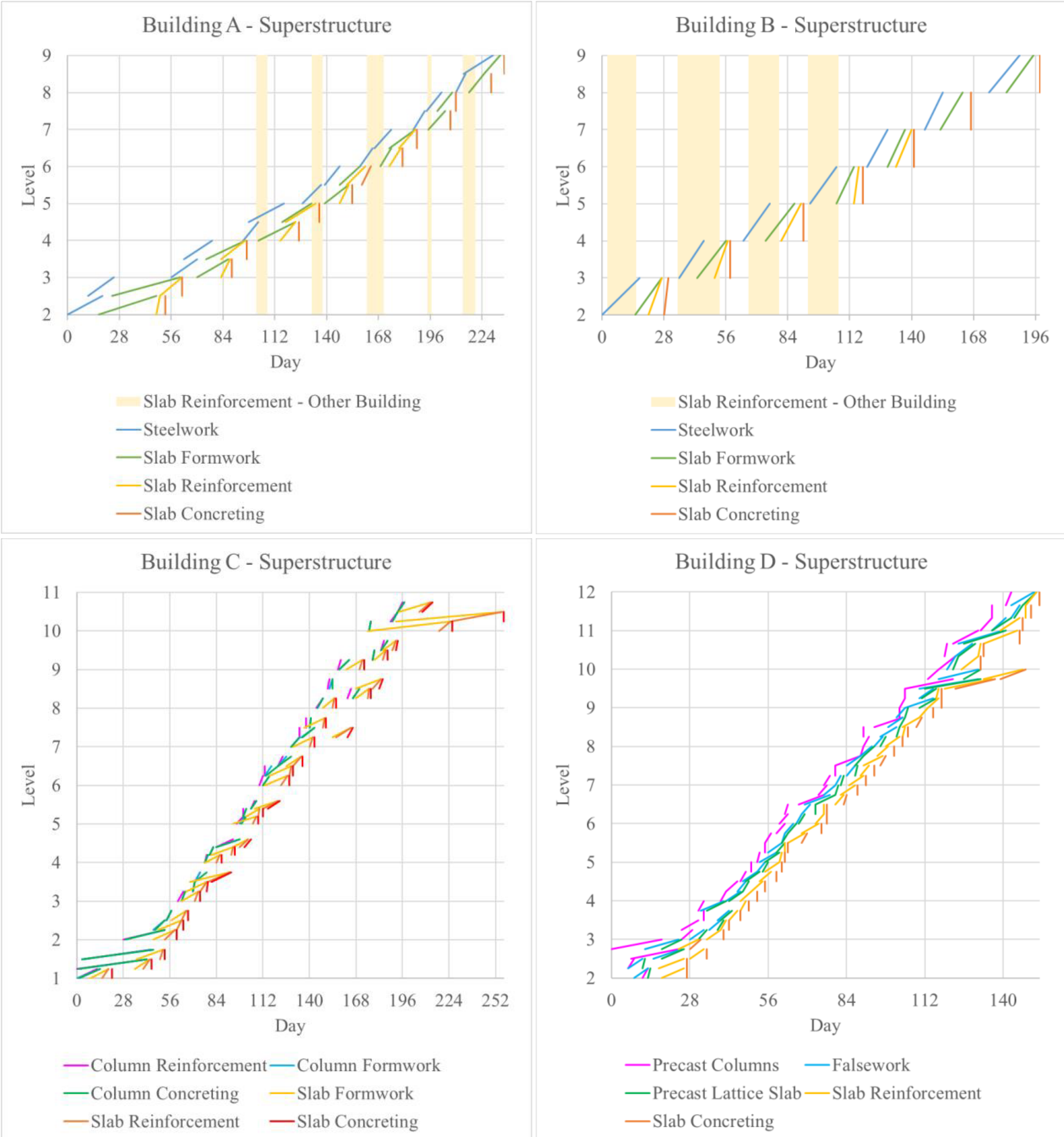

Figure 3: Flowline Charts of Building A, B, C and D Superstructure

Table 3: Correlation Results of Location Productivity with Process Flow Metrics ($p<0.01$)

Metric	Pearson Correlation Coefficient (r)	Coefficient of Determination (R^2)	Correlation Category
Excess work-in-progress time	-0.75	0.57	Strong negative
Mean location production rate	0.59	0.34	Moderate positive
Average batch size	-0.49	0.24	Moderate negative
Variability of location production rates	-0.35	0.12	Weak negative

Table 4: Correlation Results of Trade Productivity with Operations Flow Metrics ($p<0.01$)

Metric	Pearson Correlation Coefficient (r)	Coefficient of Determination (R^2)	Correlation Category
Level of work discontinuity	-0.72	0.52	Strong negative
Mean trade production rate	Not significant	-	
Variability of trade production rates	Not significant	-	

EXPLANATION OF RESULTS

Tables 5 and 6 explain the results of metrics with a relatively high degree of correlation. The regression results are explained for two hypothetical cases: a 300 m^2 location with 5 crews for process flow and a 10,000 m^2 building with 20 locations for operations flow. The average batch size is not considered as it does not appear in the regression equation, even though it has a significant linear correlation with location productivity. This might be because it does not bring additional significant information to the model. It has a moderate linear correlation of 0.56 ($p<0.01$) with the excess work-in-progress time showing similar effects on location productivity.

Table 5: Explanation of Process Flow Results

Metric	Correlation Analysis	Regression Analysis (for a 300 m^2 location with 5 crews)
Excess work-in-progress time	If the gaps between the start dates of successive activities at a location are reduced, there is a strong chance that the location's production rate will be increased.	If each of the five crews can start one day early, the overall location production rate will increase by about 4 m^2/day.
Mean location production rate	If the mean production rate of each crew at a location is increased, there is a moderate chance that the location's production rate will be increased.	If each crew can improve their production rate by 1 m^2/day, the overall location production rate will increase by about 0.1 m^2/day.

Table 6: Explanation of the Operations Flow Results

Metric	Correlation Analysis	Regression Analysis (for a 10,000 m^2 building with 20 locations)
Level of work discontinuity	If a crew can reduce the non-working period between different locations, there is a strong chance that the crew's production rate will be increased.	If a crew starts each of the 20 locations one day earlier, the overall trade production rate will increase by about 7 m^2/day.

FACTORS THAT AFFECT CONSTRUCTION FLOW

We identified several aspects of construction flow that can be improved to increase overall productivity. The question now is what factors affect construction flow. We explored one such factor: the number of locations per floor in a building. We compared the slab reinforcement and slab concreting activities which are common to the four buildings.

Buildings B, A, C and D had an average of 1, 2, 3 and 4 locations per level. In these four buildings, the slab reinforcement crews spent approximately 77%, 61%, 34% and 14% of the total days onsite without work due to the unavailability of a location to conduct work. Similarly, the slab concreting crews spent approximately 94%, 90%, 57% and 53% of their total days without work. This shows a direct inverse relationship between the number of locations per level and the level of work discontinuity. Dividing large slabs into many smaller locations can help ensure the availability of work for the crews.

This issue also has productivity implications. Site attendance records reveal that the crews were present almost every day. Still, when work was unavailable due to the unavailability of a location, they were allocated to support tasks such as cleaning and moving materials. This results in the underutilisation of skilled workers who are paid higher salaries, which is a productivity loss. We expect to uncover similar factors affecting construction flow in the future, e.g. the effect of having offsite components.

DISCUSSION

OPTIMUM SIZE OF A LOCATION

The results show that having less excess work-in-progress time, i.e. reducing the gaps between the start dates of successive activities, significantly impacts overall productivity. As mentioned earlier, having less work-in-progress is a feature of a good construction flow. Therefore, it is understandable that it leads to better productivity. However, according to the flowline charts (Figure 3), there are many locations where activities started before ending the previous activities. The results lead us to believe that having more than one crew working simultaneously at a location can improve productivity. But previous studies show that this can lead to congestion and, ultimately, low productivity (Kenley & Seppänen, 2010). The underlying issue is that all the projects in this study used traditional scheduling methods, such as Gantt charts, based on critical path techniques instead of location-based methods. There were no predefined location breakdown structures, and the locations' sizes varied across building levels and with time. Also, the planned location sizes of the buildings were too large. The average location size of buildings A, B, C and D were 626, 655, 311 and 403 m^2, respectively. These were too large for the crews who, on average, had only 4-5 workers. With these location sizes, it is possible for two or even three teams to work in different areas of a location without leading to congestion. Hence, the correlation and regression results hold. However, the goal should be to have a higher number of small locations. Using location-based scheduling could have achieved that. Murguia et al., (2023) present a more detailed analysis of this topic.

MEAN AND VARIABILITY OF PRODUCTION RATES

According to operations flow results, ensuring continuity of work or resource use strongly improves trade productivity. However, surprisingly, the results show that trade productivity is not significantly affected by the mean or variability of crew production rates at different locations. From a flowline perspective, it means that productivity is more influenced by the gaps between the flowlines and not by their gradient or the variation of the gradient. Hence, in actual projects, there is a significant opportunity to improve project performance by better dividing/sequencing the activities than by having crews work faster or more consistently. Note that the size of the dataset limits operations flow results. We are working on collecting more data to solidify these findings.

Synchronising production rates of different crews is an important step of location-based scheduling (Kenley & Seppänen, 2010). Yet, process flow results show that variability of location production rates only has a small effect on location productivity. The results might be because trade production rates (except for slab concreting) are already reasonably synchronised in the projects (see the flowlines in Figure 3). Both these results show the benefits of using actual project data for the analysis, as opposed to planned or simulated data. Our results show the construction flow issues that real projects must address to improve performance.

OTHER FACTORS AFFECTING CONSTRUCTION PRODUCTIVITY

The two linear regression equations developed have R^2 values of 0.72 and 0.52. This means the developed metrics explain 72% and 52% of the variation in location and trade productivity. There are other factors that may not be directly linked to flow-related metrics. For example, when using flowlines, we assume that crews work continuously in a location during the period denoted by a flowline before moving on to the following location. In reality, workers may not fully utilise their time due to different reasons. Moreover, some projects in our analysis used offsite components such as precast columns and composite beams. They could have also led to differences in productivity. Rathnayake and Middleton (2023) presented a review of various such factors that affect productivity. A complete model for construction productivity should include factors that are both related and unrelated to flow. Finally, construction productivity is a combination of location and trade productivity. In the future, we will explore how much each flow type can impact overall project productivity.

CONCLUSIONS

This study aimed to identify what aspects of construction flow affect productivity and quantify this impact. There are two main types of construction flow: 1) process flow, which represents the flow of activities performed at a single location and 2) operations flow, which represents the activities performed by a single trade through different locations. Using literature, we developed a set of metrics to describe these two types of flow. Then, we used the data relating to the superstructure construction of four buildings to measure these metrics. Their impact on productivity was quantified through correlation and regression analyses. The process flow was compared with the productivity of individual locations, and the operations flow was compared with the productivity of separate crews.

Four process flow metrics, excess work-in-progress time, mean location production rate, average batch size and the variability of location production rates, were found to have strong negative, moderately positive, moderately negative and weak negative linear correlations with location productivity, respectively. The linear regression equation developed using these factors explained up to 72% of the variation in location productivity. One operations flow metric, the level of work discontinuity, was found to have a strong negative relationship with trade productivity, with the former explaining up to 52% of the variation in overall crew productivity.

We found that the sizes of the locations used by the projects were too large when compared to the crew sizes. This meant that productivity could be improved by having multiple crews working simultaneously at a location. However, for better efficiency, work should be planned in smaller locations using a technique such as location-based scheduling.

This study presents initial evidence of the potential improvements in performance achievable by focusing on construction flow. We are working on strengthening the current dataset to solidify these findings. In the future, we expect to expand these findings to cover other work packages and other aspects of flow.

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THE PICO FRAMEWORK FOR ANALYSIS AND DESIGN OF PRODUCTION SYSTEMS FOR CONSTRUCTION

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ABSTRACT

PICO is a framework that provides a conceptual guide for production system analysis and design in the construction industry. It has four key components: Production control mechanism, Information and communication system, Commercial terms, and Organizational structure. Each component is highly interdependent and has a set of detailed parameters and enumerated values. A comprehensive literature review, case studies, and analysis highlighted the knowledge gaps in current production system design frameworks. The PICO framework was originally devised to design a production system suited for short-takt production in residential construction, but it has been developed into a comprehensive mapping tool for the design and analysis of construction production systems in general. The paper shows an application of the framework to a takt system as a case study and an example of its application. The framework expands the current understanding of production systems in construction, offering new insights and a comprehensive approach to designing new production systems.

KEYWORDS

Production system design, production planning, and control, residential construction, Integrated Project Delivery (IPD), Transformation-Flow-Value (TFV).

INTRODUCTION

Production systems consume inputs (people's work, capital, information, equipment, materials) to produce goods and services by integrating physical and information flows constrained by capacity and other limitations (Nahmias and Cheng 2009). The Lean construction community has long advocated for greater control over operational flows in the production system to reduce waste and improve efficiency (Wandahl et al. 2021).

Current understandings of production systems in construction rely on the Transformation, Flow, Value (TFV) theory (Ballard et al. 2001; Koskela 2000) and the Lean Project Delivery (LPD) approach ("Lean Project Delivery" 2023). The TFV theory proposes that its three concepts should be integrated and balanced to optimize the production system. The theory

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serves as a tool for conceptualizing production system performance, supporting efforts to identify and eliminate waste (Bølviken et al. 2014). While TFV is useful in detecting waste within the production system, it does not provide a structured framework to identify and configure production systems systematically. The LPD project management approach strives to enhance flow and diminish waste ("Lean Project Delivery" 2023) through the presentation of principles that can be implemented in various forms.

The PICO framework presented here is a tool for applying the LPD methodology through use of a set of detailed parameters based on TFV theory. The framework provides a detailed view of the existing decision variables involved in designing a production system in construction. In the current era, with various lean methods available, the PICO system offers a comprehensive approach that allows the designer of a production system to characterize the way to achieve LPD goals. The framework aims to define the interrelationships between production system components comprehensively and holistically. We first present the background and research methodology, followed by the PICO framework and a case study demonstrating the framework's application in a residential project in Finland.

BACKGROUND

The PICO framework supports the development of production systems within the construction industry while aiming to bridge the current knowledge gaps. Implementing lean construction methods marked a significant shift in the language of production within the construction industry, affording managers a fresh perspective on the production system. However, while several theoretical frameworks such as TFV and LPD were developed in this regard, they lacked the necessary level of detail and did not furnish operational tools for applying the principles (Ballard et al. 2001). Consequently, any stakeholders tasked with providing solutions to pertinent issues were left wanting information on the mutual effects and available possibilities. Furthermore, the industry's attitudes toward technology and its role in production have not changed significantly over the past two decades. This chapter thus presents the historical backdrop of the construction production system theories upon which the current production systems are built and present the knowledge gap the PICO framework aims to bridge.

HISTORICAL OVERVIEW

The history of the design of production systems in construction can be traced back to the early 20th century when the construction industry started adopting industrial production principles to increase efficiency and improve productivity. This was exemplified by the use of assembly line techniques in constructing skyscrapers in the US in the 1920s and 1930s, which allowed for the efficient and coordinated construction of large-scale buildings (Sacks and Partouche 2010; Ward and Zunz 1992). In the 1950s and 1960s, the industry embraced advanced production techniques such as prefabrication and modularization to manufacture building components off-site and reduce construction time (Hashemi 2013). In the 1970s and 1980s, construction researchers and practitioners developed formalized models and frameworks, including the influential Construction Industry Institute's (CII) "Research Team" model (Tucker 2007).

In the 1990s and 2000s, the construction industry continued to evolve, and production system design became increasingly important as global competition increased and the need for cost-effective, high-quality construction solutions became more pressing. In response to this, researchers and practitioners developed several new models and frameworks, such as the Integrated Project Delivery model (IPD)("Integrated Project Delivery: A Guide" 2007). These models emphasized the importance of collaboration, communication, and integration to achieve optimal project outcomes.

LEAN PRODUCTION SYSTEM

Lean construction production methods and systems are increasingly popular in academic and research settings due to their proven ability to enhance productivity (Howell and Ballard 1998; Thomas et al. 2002; Wong 2018). In the construction industry, production systems refer to the methods and techniques used to organize and manage the various processes involved in construction projects (Ballard and Howell 1998). Koskela (2000), offered a lean theory of production, conceptualizing it through the lens of the Transformation, Flow, and Value (TFV) views. The TFV approach highlights the importance of maximizing value, minimizing waste, and efficiently producing the product. Transformation focuses on converting inputs to outputs. Flow considers the flows of materials, resources, information, and products through space and time, and the Value pertains to methods for capturing requirements and achieving quality in the eyes of the consumer. Ballard et al. 2001 proposed a set of business objectives for project-based producers based on the TFV theory, which instructed adopters to “Align stakeholder interests” or “Reduce variability”, for example. These guidelines provide a valuable decision-making framework covering various global organization production aspects.

Subsequently, it was recognized that incorporating changes during production without considering the integration between stakeholders in the production process was a challenging task. The IPD contract method was developed to address this issue (“Integrated Project Delivery: A Guide” 2007). It is a collaborative project delivery approach that involves the owner, designer, and builder working together as a team from the early stages of a project to achieve project goals, such as reducing waste, improving quality, increasing efficiency, and maximizing value. IPD is based on a shared risk-and-reward contract that promotes collaboration and communication among team members. The primary objective of IPD is to create an integrated and efficient project delivery process that benefits all stakeholders.

Mossman (2010) introduced a model with three domains that apply to every construction project, as illustrated in Figure 1. This production system design model emphasizes the critical need to consider and align the commercial terms, operating systems and organizational structures to implement the Lean Project Delivery approach (“Lean Project Delivery,” 2023). A lean project's success depends on effectively integrating the elements of these domains.

Figure 1: Production system design in construction (Mossman et al. 2010, p.10)

The organizational domain involves the integration of the owner, designer, and contractor. The operating system refers to the implementation of production control methods and tools, such as the Last Planner System (LPS), Value Stream Mapping (VSM), and Building Information Modelling (BIM), and the commercial terms pertain to the incentives of the various stakeholders, such as the traditional Design-Bid-Build (DBB) model prevalent in the industry, Design-Build (DB), Collective Risk Management, and Profit and Loss Sharing.

These theories and frameworks present objectives and low-resolution production system design guidelines. There is no comprehensive tool that categorizes and clusters the variables of each domain to offer a holistic understanding of the interdependence of every decision made. The theories presented in the literature lack a comprehensive framework that can be practically applied to an operative production system and an understanding of the interconnectedness within the system.

RESEARCH AIM AND METHODS

The aim of this work was to devise a new conceptual framework for production system design that considers all aspects of the project, including people, methods, means, economics, motivations, and the interactions among them.

We employed a two-cycle methodology (Figure 2) following the iterative improvement principle of design science research (Hevner 2007). The first is the Explore cycle, and it comprises three iterative steps: 1) qualitative analysis of the literature and previous studies on construction production systems, 2) observing current production systems from case study projects in literature and other self-collected projects, and 3) examining the current paradigm of production system design through the findings from the first two steps. The second is the Elaborate cycle, in which we consolidate the learnings from the Explore cycle to arrive at a coherent and holistic production system design framework. The three steps within this cycle are 1) devising a list of production system design parameters, 2) validating the framework through case studies, which involved site visits, interviews with project managers and foremen, and workshops with senior management of the construction company, and 3) co-creating production system design concepts through discussions with the construction company.

In the following sections, we present our proposed conceptual framework, explaining each component in detail. Then, we apply this framework to a case study residential project in Finland to demonstrate how it can contribute to the analysis and improvement of the production system design.

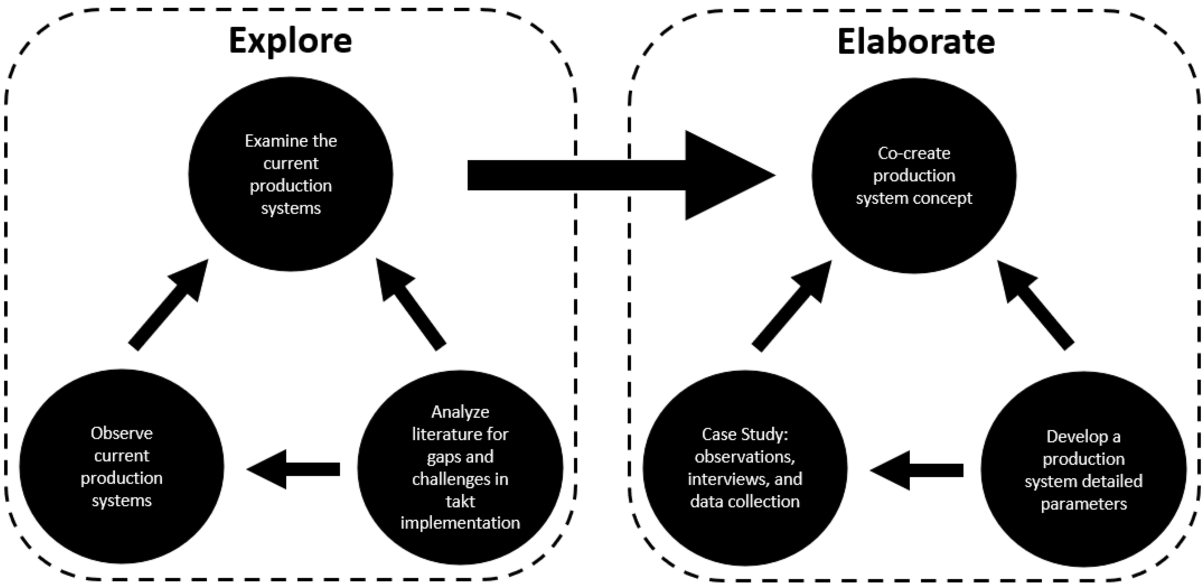

Figure 2: Research methodology (adapted from Hare et al. 2018).

A NEW CONCEPTUAL FRAMEWORK

To address construction projects' complexities and their dynamic nature, we propose a new conceptual framework for production systems that considers all aspects, including people, methods, means, economics, motivations, and their interactions. The framework, designated with the acronym 'PICO', consists of four components: (P) Production Control Mechanisms, (I) Information and Communication Systems, (C) Commercial Terms, and (O) Organizational Structures, presented in Figure 3. The full PICO framework is defined in an Excel worksheet that provides a detailed breakdown of the parameters relating to each part of the production system, descriptions and a set of possible values for each parameter. This tool serves as a map of decision variables in the design of a production system for construction. Through this approach, we can identify underlying issues and develop solutions that consider the interconnectedness of the production system. The framework considers adoption of lean principles and new monitoring technologies.

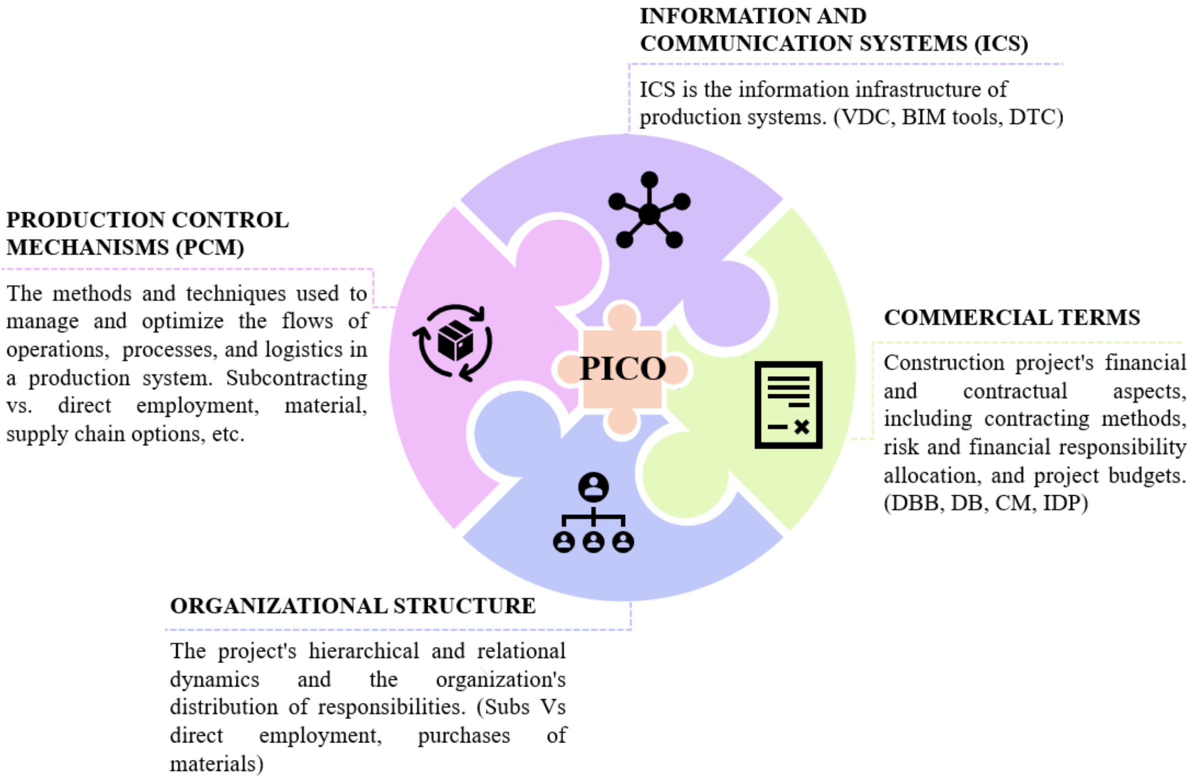

Figure 3: PICO Production System Design Framework

P - PRODUCTION CONTROL MECHANISMS (PCM)

PCM refers to the methods and techniques used to manage and optimize the flows of *operations*, *processes,* and *logistics* in a production system. PCM encompasses the 'operating system' concept defined by Mossman et al. (2010). . Among operating system tools, there are the Critical Path Method (CPM), Location-based Management Systems (LBMS), Last Planner System (LPS), Virtual Design and Construction (VDC), pull methods, Takt scheduling, and combinations of them (Kenley and Seppänen 2009; Scala et al. 2022).

Operations flow refers to the flow of production resources, such as labor and equipment, flowing through time and space (Shingo 1989 p.3).

Process flow refers to products within a building, such as apartments, classrooms, or hotel rooms, or road sections, such as bridges, lanes, or ramps. These serve as the units of production in construction and can be considered analogous to the individual products that are defined in Shingo's process-oriented definition. The policy driving process flow should seek continuous flow for those products, with zero waiting times of the products between activities, to optimize throughput, reduce cycle time and minimize Work-in-Progress (WIP) (Ballard 2001; Sacks 2016). This aspect is often neglected in traditional construction systems. Note that the units of production (products) are not the same as the locations in a location-based planning system (Kenley and Seppänen 2009), although in some cases, they may overlap.

Logistics flow refers to the movement of consumable resources, such as consumable product information (e.g., shop drawings) and raw materials, through time and space. The nature of construction sites necessitates distinguishing logistics as a flow in its own right. Good logistics flow implies managing the movement of materials so that suitable materials are delivered to the correct location at the right time in the appropriate quantity. Logistics necessitates a distinct operational approach and may involve prefabrication, pre-assembly, or fabrication on-site.

I - Information and Communication Systems (ICS)

ICS is the information infrastructure of production systems. Whereas all construction companies use basic digital tools – databases and design and detailing software, scheduling and accounting systems, and so on – many apply more sophisticated production systems, often with VDC, cloud-based information control, and site monitoring technologies. Project management tools like VICO, VisiLean, and SiteDrive are applications of these concepts used to accomplish production system goals. When designing a new production system, appropriate and effective integration of ICS is essential. Advanced ICS are indispensable for developing future production systems such as Digital Twin Construction (DTC) (Sacks et al. 2020).

C - Commercial Terms

Commercial terms refer to a construction project's financial and contractual aspects, including contracting methods, risk and financial responsibility allocation, and project budgets. The most common commercial terms in the construction industry include traditional methods such as Design-Bid-Build (DBB), Design-Build (DB), and Construction Management at Risk (CM), which differ primarily in terms of the level of risk and financial responsibility assumed by each party. Choosing the appropriate commercial terms is central to enabling the desired production system and depends on factors such as a project's size and complexity, the available resources, and the specific design and execution requirements. The commercial terms between the general contractor and trade crews who perform work, including employment conditions and compensation, as well as the purchasing and procurement of materials and assignment of risk, are pivotal in the design of the production system. They significantly impact a system's overall efficiency and effectiveness and should be carefully considered, crafted, negotiated, and agreed upon.

O - Organizational structure

The organizational structure pertains to the project's hierarchical and relational dynamics and the organization's distribution of responsibilities. For instance, the General Contractor (GC) may employ the project manager, foremen, subcontractors, or workers directly or as independent subcontractors, while the logistics and material supply management may be delegated to the GC or subcontractors. The organizational structure serves to clarify the roles and responsibilities of everyone involved in the project.

Overview

Table 1 provides a partial view of the PICO framework breakdown of its aspects and their parameters (the complete framework is available online - (Sharoni et al. 2023)The framework supports comprehensive planning for, and examination of, any project's production system components and interdependencies. The first two columns in Table 1 display the system aspects and their parameters. The third column provides the parameter values for a case study, which will be detailed in the next section.

Every decision made during the design of a new production system must consider the interdependence of its components and the tools available for its development. For instance, when setting a contract with subcontractors, the parameters must include factors such as the expected work rate, responsibility for delivery of materials to the site, procurement of materials, work performed on and off-site, budget, schedules, methods of communication, and human resources management. The contract should also address the type of payment, payments for changes during work, etc.

Table 1: Applying part of the PICO framework to a case study project. The complete framework is available online (Sharoni et al. 2023)

Aspects	Parameters	Case Study Example: Weekly Takt Residential Project
	P - Production Control Mechanisms (PCM)	
Work Packaging	Location Decomposition Work Breakdown Structure Product Decomposition Scheduling Buffer Policy	Floor and building Trade specialization Floor and building One hour
Production planning and control methods	Look ahead planning/ constraint filtering Short-term work planning	CPM; Last planner system - workable backlog CPM; Last planner system - WWP, PPC
Product changes	Coordinating Documenting	Daily meetings, WhatsApp, and E-mails Self-report to a digital platform (Sitedrive)
	I – Information and Communication Systems	
Operations flow information	Trades (Workers) production rate	Experienced based trade type production rate
Process flow information (Product)	Product fabrication information LOD requirements Product detailing process	Medium (LOD 300) Subcontractors provide shop drawings for review
Logistics flow information	Materials location monitoring frequency Control Technologies	Weekly Digital self reporting
Platforms/ Software	Production status dashboard system Schedule Procurement	SiteDrive Word, Excel, Miro, Sitedrive BIM models, e-mail, Zeroni, WhatsApp
	C – Commercial Terms	
Contract	Type Intervening Phase	DBB Final design
Control and flexibility	Design Control Flexibility for changes	Limited Minor changes
	O – Organisational Structure	
Hierarchy	Departments/Groups/Crews	Developer, Clients (apartment purchases), Design, IT, Accounting, HR, Procurement (includes safety and quality), logistics, and suppliers.
Functional role parameters	Deliverables	Developers, Designers, Accounting, Procurement, business unit managers, site managers, foremen, subcontractors, trades, team leaders, workers, and suppliers.

CASE STUDY: TAKT SYSTEM FOR A RESIDENTIAL PROJECT

This section examines the application of the PICO framework to a case study project of a residential building project in Finland that implemented a weekly takt time approach during the interior phase. The construction company responsible for the project, FIRA Oy, reported a 20% reduction in project duration thanks to use of the takt method. However, it was noted that there were still opportunities for further improvement. Why did the production system fail to achieve the throughput aims of its designers? The PICO framework enabled rigorous analysis of the weaknesses of this case study system, as detailed below. The parameter values for the case study project are available online (Sharoni et al. 2023).

PRODUCTION CONTROL MECHANISMS

FIRA Oy utilizes a variety of control mechanisms in its production systems, including Location-based Planning and Control, Last Planner System (LPS), and takt scheduling. When implementing takt production, FIRA employs lean principles that have been partially adapted to suit the company's nature, prevailing market regulations, and cultural factors.

Operation: Trades and constraints between them are identified and implemented in a master schedule that maintains a weekly takt. While the schedule aims to present the workflow, not all trades and tasks are planned nor appear, causing a lack of documentation and an inability to monitor essential work. The takt schedule shows dominant trades but not prerequisite tasks performed by other small trades and subs, such as measurement and marking, drilling openings, sealing of openings, etc. Moreover, installing windows takes one working day per floor; yet the planned takt schedule allows the trade a week. Thus, there is work waiting for workers most of the week. Even if the trade is requested to arrive on a particular day, the trade arrives during the week subject to prioritization of other commitments. The rest of the week is dedicated to prerequisite work that was not on the schedule. The prerequisite task implementation depends on the site team's knowledge, experience, and vigilance. The extension of buffers allowed the site crew to prepare and complete the prerequisite tasks, maintaining the planned operation flow, increasing flexibility, and exhibiting a higher tolerance for errors and coordination problems. The example points out the lack of (1) detailed operation design, (2) incentive for subcontractors to arrive on time when they are aware of the project's flexibility, (3) and lack of preserving professional organizational information. All three hinder reducing the takt and will find an answer in the other PICO domains.

Process: The chosen production unit for the case study building is a floor that aligns with the location breakdown structure (LBS). The production process aims to establish a manufacturing methodology with minimal variation between floors and a work breakdown structure (WBS) comprising 300 tasks. Reducing the production unit to a room would significantly increase the number of tasks involved in planning, operating, and monitoring, as arranging different trades in the same apartment would present safety and logistics operations challenges. Manual planning of 300 tasks is already a human challenge, and extending this to over 10,000 tasks in a full-scale project would be infeasible without an automated tool.

Logistics: The procurement department, site team, and subcontractors retained responsibility for purchasing materials. However, the material ordered by the procurement department was delivered to the site by a logistics company in pre-packaged kits aligned with the LBS. This allowed for efficient delivery control as the kits were delivered directly to the operation location, reducing handling and obviating the need for storage areas. Efficient logistics support is crucial for successful takt production but requires significant resource investment. The benefits include lower transportation costs, reduced waste, and high team satisfaction. However, advanced material information is necessary for successful implementation, and last-minute orders cannot be accommodated.

INFORMATION AND COMMUNICATION SYSTEMS

The production system's schedule was created using Tocoman (https://www.tocoman.fi/) software, detailed in Word and Excel, planned on a Miro board, and then manually transferred to the SiteDrive platform. Foremen then further detailed the schedule on Excel and SiteDrive. The project design models were compiled with BIM software, and the on-site communication used 2D drawings that were updated whenever significant changes were made. Small changes or clarifications regarding details were done through direct communication and were not continuously updated in the model. The project manager was required to use multiple platforms for functions like financial planning, logistics, coordination with designers, quality and safety control, procurement, and more. Even in the best-case scenario, these platforms are only marginally interoperable. This lack of integration leads to prolonged planning, increased risk of human error, and low-resolution work, ultimately transferring responsibility to the next person in the production chain. Efficient information and communication systems have been recognized as crucial in reducing and accelerating takt production. To effectively implement shorter takt, less than a day, it is essential to have access to detailed design information and a seamless connection between procurement and material location systems. In addition, real-time progress updates, supply chain information, and the ability to quickly adapt to unexpected events are crucial in achieving success.

COMMERCIAL TERMS

The company's commercial terms with the owner are those of a DBB contract. The fixed design limits the company's ability to adapt to its production capabilities and planning priorities. Labour (subcontracted crews) are compensated using a piecework product-based system. However, in the event of any delays caused by the GC, additional payment in the form of hourly compensation may be provided to the subcontractors. The company employs specialized trade labor crews with a specific scope of professional responsibility. While prefabrication is challenging for interior construction phases, the bathrooms of all apartments (excluding those with saunas) were prefabricated in a factory, complete with all finishes, sanitary equipment, tiles, showers, and mechanical systems, ready for delivery and installation. The company works with the subcontractors using an open book method and invests in higher wages. However, the company needs to examine the correct contract method between the GC and the subcontractors, both in the scope of work type (multitasking, cleaning) and the payment method, to balance buffers implementation and payment for empty work slots.

ORGANIZATIONAL STRUCTURE

The project's organizational structure is an intricate network of connections and interactions between various stakeholders. The owner is responsible for hiring the design team and the GC. The GC communicates with subcontractors through its procurement department and its site team, which oversees the site operations. The GC also operates a logistics centre, where materials are packaged and delivered directly to the operation location to ensure efficient delivery control. The subcontractors provide specialized trade crews with a leader for each trade. Although the traditional three-party structure of owner, GC, and design team still holds, the complexity of the GC's production system expanded the project's organizational structure. Like many other companies, Fira experiences disconnection between headquarters and the site team. The soft element of an organizational structure is challenging to research and measure, connecting people and processes. However, the research indicates that the headquarters' process to implement new work methods and technology, such as takt, does not align with the understanding and needs of the site team. Additionally, duplication of purchasing responsibilities, for example, between subcontractors and the company, and contradictions between managers and internal customers hinder the implementation of changes, efficient information flow, and improvement.

From this analysis, it becomes apparent that certain parameters contribute to the optimization of the production system, such as the implementation of large buffers due to the non-detailed planning of the schedule. Conversely, other parameters can cause delays, such as a lack of planning detail. Increasing the level of planning detail can shorten the takt, reduce buffers duration, and enhance control over the production process. However, to increase the level of process detail, several requirements must be met, including greater control over product design, increased involvement of the GC, and the collection of preliminary information on the contexts and limitations between trades. Nevertheless, increasing detail alone is not sufficient to translate it into a significant financial advantage. A control system is also required for short-term management that includes the management of tasks, manpower, and materials. The case study, together with the parameters outlined in the accompanying Excel sheet, presents a complicated and intricate production system. Nonetheless, this framework provides a crucial starting point for comprehending and mapping production systems in the construction industry.

DISCUSSION AND CONCLUSION

A comprehensive approach to production system design in construction is needed, one in which every possible modification within the system is considered part of an interconnected network. To design any new production system for construction, such as a short-term takt system, for example, it is crucial to evaluate the entire production system, including aspects such as the role of the general contractor in the early design phase, the establishment of a logistics canter, the integration of technological tools to enhance takt planning, and the formation of a new organizational structure with dedicated departments. These innovations should be adopted strategically and holistically, considering their impact on the overall production system, including the flow of resources, communication, collaboration among stakeholders, and technology integration in construction processes.

The components and parameters outlined in the PICO framework are interrelated and interdependent, and their values should be set holistically. New technologies or methods should not be implemented in isolation, but rather as parts of coherent systems. In today's fast-paced and ever-evolving construction industry, incorporating a new tool for monitoring the construction process or adopting a new approach like takt, without considering the underlying production system structure, can lead to limited or suboptimal results.

This paper emphasizes the importance of redesigning the production system structure. The literature argues that the role of human capital within the production system is the key factor in a manufacturing industry's success, perhaps even more than the production system design itself, as the company's success depends on the efforts and capabilities of its intellectual capital and its staff's ability and capacity to innovate (Fane et al. 2003). However, when internal structural conflicts impair a system and the system lacks mechanisms for control, operation, management, and forecasting, even the most talented and skilled individuals may have limited ability to succeed.

Note that, although this paper presents the framework for production system design and details the PICO domain parameters and the connections between them, due to space limitations, a comprehensive analysis of the full impact of each parameter on the others is beyond the scope of this paper.

In conclusion, the challenge of improving the construction process is significant, and many possible solutions exist. However, clearly defining and understanding the issues at hand is essential, and the goal of the PICO framework is to enable just that. This work contributes to the scholarly community by expanding the current understanding of production systems in construction and presenting a new framework for defining and implementing new production systems, such as shorter-term takt production. The clear definition of construction products as distinct from locations is a key feature of the PICO framework and should enable standardization of work. A sequel paper will present the application of the framework to compare four different production systems and the consequent derivation of a production system with a takt time of one day or less.

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IMPLEMENTATION OF LEAN THINKING TO IMPROVE MASONRY CONSTRUCTION AND DESIGN

Samaneh Momenifar[1], Karl Keyrouz[2], and Farook Hamzeh[3]

ABSTRACT

Masonry construction provides multiple functions with a single element, is cost-effective, durable, and provides a visually appealing finish. In addition, its flexibility in design and reasonable construction cost makes it more attractive. Specifically, characteristics of load-bearing masonry make it a viable choice for residential buildings, hence a viable solution to address housing demands. However, evidence shows this type of building is less desired nowadays due to its reputation as having traditional shapes and low productivity in the construction process.

Lean thinking has been widely applied in the construction industry. However, lean applications in the masonry industry can be widened. In this research, site visits, consultations with industry professionals and stakeholders, and an extensive literature review have been conducted to understand existing problems of design and construction of load-bearing masonry systems in Canada. To address the discovered problems, several lean thinking solutions are proposed with the focus on consideration of complex wall configurations and providing early feedback in the conceptual design stage of masonry buildings. Development of one-piece flow for mortar transportation and generative design tools are two of proposed solutions. Development of intelligent BIM and construction simulation models are presented as future research ideas to validate the proposed lean solutions.

KEYWORDS

Masonry, generative design, simulation, lean thinking.

INTRODUCTION

Compared to other structural systems, masonry's competitiveness is threatened by several myths and assumptions architects hold, such as the high cost of masonry construction and its constrained formal options (Gentry et al., 2009). Waste in the construction industry leads to many problems, such as decreased productivity, cost overruns, schedule delays, and safety issues (Senaratne & Wijesiri, 2008). Also, productivity assessment implemented on the masonry construction process revealed low productivity and waste in this type of construction. The presence of waste negatively affects the value delivered to customers (Abbasian Hosseini

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et al., 2012). Moreover, more recent studies also show the factors that most affect masonry construction are related to rework and lack of safety, required tools or material on a construction site (Svintsov & Abd Noor, 2022) which further leads to waste on construction sites and consequently decreases the value produced for the customer. Implementing lean principles in construction processes can help to identify non-value-adding activities and improve the process, as demonstrated in the masonry industry. Implementing lean construction principles has been shown to reduce waste and improve cycle time and efficiency (Abbasian-Hosseini et al., 2014).

Masonry-bearing walls have a long history in construction, dating back centuries, and have been used in various building types, from simple structures to grand monuments and public buildings (Cross, 1965). During the early 20th century, brick construction for multi-story buildings was primarily replaced by steel and reinforced concrete framed structures, but brick was often used as cladding (Hendry et al., 2017).

The decline in the popularity of masonry construction is believed to have been caused by the introduction of new materials and construction methods, the desire for faster construction, and the development of new load-bearing structures and lightweight facade systems (Sweis et al., 2008). According to our investigation, the decline in masonry construction in Canada is attributed to several reasons, some of which are presented in the literature review. The rest are spotted in construction site visits and consultations with industry practitioners. This paper aims for lean improvements in the current state of masonry in three categories: masonry design, construction, and unit. In masonry design, the design fixation phenomenon is presented as a significant challenge in the current design practice of masonry systems. This leads architects to opt for more straightforward and more conventional solutions instead of innovative ones. Integrating Building Information Modelling (BIM) and generative design can help overcome this by providing architects with a tool to design complex masonry walls that are structurally feasible and constructible. Many innovations have happened in masonry units, including materials, systems, mortar additives, ties, and reinforcements. The recent introduction of masonry units with integrated insulation has gained significant attention in the industry, offering a simpler and more streamlined construction process. The use of alternative masonry blocks that do not require cement and moving towards panelized construction in the design of new masonry units is recommended in this category. In masonry construction, the current implementation of lean in the masonry industry has proven to be effective in reducing waste and increasing efficiency. However, the complexity and variability of wall configurations, especially L-shaped and T-shaped walls, have posed challenges to implementing lean in the masonry industry. The future of masonry construction can be improved using lean thinking steps here. Some of these steps are developing a just-in-time schedule for bricks and mortar components delivery and using pull-driven scheduling when planning the bricklaying of different sections of a building composed of Concrete Masonry Units (CMUs).

LITERATURE REVIEW

Masonry load-bearing walls have a long history of use in construction, dating back centuries. They have been used in many building types, from small, simple structures to grand monuments and public buildings (Cross, 1965). Brick construction for multi storey buildings was replaced by steel- and reinforced concrete-framed structures in the first part of the 20th century, but they were frequently covered with brick (Hendry et al., 2017). The John Root-designed Monadnock Building in Chicago, which stands sixteen stories tall and has walls that are 1.82 meters thick at the base, was "the final triumph of traditional masonry building" in 1891 (Cross, 1965).

It is believed that the introduction of new materials and construction methods, the desire for faster construction with fewer workers on-site, and the development of new load-bearing structures and lightweight facade systems have led to a decrease in the popularity of masonry (Sweis et al., 2008). One of the leading causes of this was that solely empirical criteria were used for proportioning load-bearing walls up until around 1950. It resulted in unnecessarily thick walls that wasted material and space and took a long time to construct (Sinha, 2002). The development of structural codes of practice, which made it possible to determine the required wall thickness and masonry strengths more reasonably, improved the situation of masonry buildings in several countries after 1950. Although initially limited in scope, these standards of practice were based on research projects and building experience. They offered an adequate framework for the design of structures up to thirty stories. The development and enhancement of the various structural codes for masonry structural design over the past 20 years has resulted from extensive research and real-world experience. Because of this, the structural design of masonry buildings is getting closer to being on par with steel and concrete (Hendry et al., 2017).

In terms of architectural design, modern architecture conflicts with masonry. Using steel or concrete frames and curtain wall skins in construction has led to the dematerialization of design, while masonry construction is rooted in using materials. This user has created an ambivalent relationship between modern architecture and masonry (Collins, 1998). In addition, there is a notion that architects are not pushing the boundaries of masonry, even though the masonry business and research community have consistently advanced with improvements. Such improvements aim for new masonry unit types with sustainable and green construction and integrated insulation (Subasic, 2022), structural analysis methodologies, and more effective building procedures (Beall, 2000; Beall & Jaffe, 2003). It has been noted by Heyman (Heyman, 1996) that the decline in masonry as a building material has led to a decrease in expertise and knowledge in masonry design, detailing, and construction, particularly in the use of non-planar forms of load-bearing masonry structures. Researchers (Gentry et al., 2009) claim that the perception of masonry as a conservative and risky building technique when aiming for innovative shapes, combined with a shortage of specialized knowledge and computational tools, limits its acceptance and acceptance ability to compete with other building methods. Therefore, most new masonry buildings use traditional and conservative solutions.

The sequential and complex construction process of masonry buildings causes inconsistent information flows in design and construction. Design management entails managing the flow of information and coordinating individuals and teams involved in the design process (Al Hattab & Hamzeh, 2018). Design workflow consists of transferring information and deliverables between teams and individuals, and it has become more complex due to advancements in design specifications, end-user needs, and technology. The production of large amounts of information and the pressure of deadlines and budgets increases the risk of design errors and conflicts. Poor design flow can lead to several types of waste, including excessive rework and revision cycles, design errors, reduced quality, increased costs, and schedule delays, ultimately decreasing the value generated for end-users (Ballard, 2002).

It is confirmed by industry practitioners in Canada that masonry wall systems are facing competition from other wall systems such as wood, glass, steel clad, and precast (Jordan Kuntz, 2022). According to our site visits and consultations with industry practitioners, there are multiple reasons behind this phenomenon, some of which are mentioned in the literature. In this paper, reasons behind the decline in the prevalence of masonry use are presented into three categories: masonry design, masonry unit, and masonry construction.

METHODOLOGY

Building with masonry requires significant manual labor, and the implementation of innovative solutions needs to be expanded. Another hurdle facing the masonry industry is the unawareness of new masonry forms and construction techniques by professionals in the field. This study evaluates the current construction and design methods used in masonry construction and the possible lean improvements that can be applied in the industry. The authors hypothesize that by looking at the design and construction of masonry systems, it is possible to provide potential lean solutions that will be of value to the industry and the professionals in it. Lean principles have already been implemented in the masonry industry, but their current applications have been limited. As such, this study presents what has been done in the masonry industry to improve the design and construction of masonry systems and the potential possible lean applications. The reviewed literature first identifies the research problems. Then, multiple construction site visits, consultations with masonry industry practitioners, and the conducted literature review formed the basis for recommending lean solutions. These lean thinking solutions are hoped to decrease waste in design and masonry construction practices. The methodology diagram developed by the authors as a research framework is shown below in Figure 1. In the first phase, a literature review on design principles of masonry systems and lean improvement is conducted. Then, several site visits from masonry construction projects and discussions with superintendents and masons are implemented. Consultations with active industry practitioners were the last step of phase 1. During phase 2, authors tried to address the discovered problems with lean solutions, and in the previous phase, future research opportunities for implementation and validation of proposed lean solutions are presented.

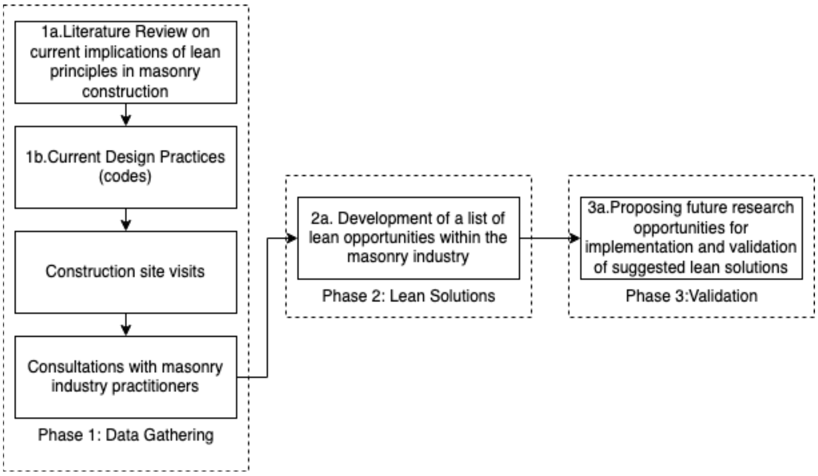

Figure 1: Research Methodology

To develop a list of lean opportunities in the masonry industry, site visits were performed to identify the problems currently affecting masonry productivity and, more specifically, in the bricklaying process. In addition, in a 2-day masonry Hackathon held at the University of Alberta, discussions with industry stakeholders and professionals of diverse backgrounds in naming, structural, thermal efficiency, and robotics brought to light some previously unknown aspects of existing problems in the masonry industry.

MASONRY DESIGN

Researchers claim that a phenomenon known as design fixation (Jansson & Smith, 1991; Purcell & Gero, 2006) is happening in current masonry design due to lack of early feedback: The lack of early feedback during the conceptual design stage can result in uncertainty, leading architects to avoid unusual and potentially more innovative solutions and instead opt for more straightforward and more conventional solutions. This is more likely when the number of parts involved in a problem is high, such as in the case of a masonry wall, cladding system, or tiled roof. Furthermore, the tendency to follow conventional configurations is often justified by adhering to traditional construction wisdom (Cavieres et al., 2009), which can result in a missed opportunity for innovation and progress in the design and construction of masonry structures. Hence, it is essential for architects to have access to the necessary knowledge resources and to receive early feedback during the conceptual design stage to help guide their decisions and minimize the risk of design fixation (Cavieres et al., 2011). The authors conclude that when masonry designers are equipped with constructability knowledge of innovative masonry configurations, the state of masonry in both design and construction will be significantly improved.

However, masonry designers have a limited number of digital tools at their disposal to represent and investigate novel brickwork arrangements. The amount of work architects must spend modeling and detailing a building with hundreds or thousands of masonry components becomes expensive without such technologies (Bettig & Shah, 2001). This means current technological advancements are not being widely adopted into masonry design practice.

BIM is expected to revolutionize the construction industry by introducing more standardization, consolidation, and integration in the construction process. BIM will shift the construction process from being project-based and reliant on unique customer specifications to a more product-based approach, utilizing off-site manufacturing and prefabrication (Heigermoser & de Soto, 2022). BIM will enable the integration of generative design solutions, a design approach many researchers have proved effective in creating more creative masonry wall configurations. Masonry units offer a wide range of configurations and formal results, which can be intensively explored through parametric modeling, making the representation of complex geometries and assemblies easier and more realistic, leading to innovation in the design of masonry buildings. Some research focuses on promoting the use of concrete masonry systems in contemporary design practice by incorporating masonry construction knowledge into the design process through state-of-art computational technologies. The goal is to improve the design and construction processes by enabling the creation, testing, and evaluation of a more considerable number of design alternatives from the start. This way, an important focus will be on building envelopes' formal variability and geometric complexity. The methodology described is a simplified system that helps architects design complex masonry walls in the initial stages of the design process. The system uses continuous updates in a CAD environment and Building Information Model to validate, shape, and bind architectural decisions. Its purpose is to provide architects with a tool to design structurally feasible and constructible walls, giving them confidence in their design decisions (Gentry et al., 2009).

Generative design (GD) is a computational design method that uses algorithms and parameters to generate a range of design solutions based on specified constraints and objectives. The process involves inputting design criteria, such as desired functionality, material properties, and manufacturing limitations, and then allowing the computer to generate and evaluate different design options. The final design solution is chosen based on the best combination of performance, cost, and other factors. Integrating generative design and BIM combines the benefits of both approaches to create a more efficient and effective design process (Nagy, 2020). By combining the intelligent design capabilities of generative design with the automated construction information generation of BIM, the GD-BIM integration can help ensure that the algorithm's designs are feasible and constructible. At the same time, it can enhance the BIM's capabilities in the early design phase by providing more accurate and detailed design information. This results in a more streamlined design process that saves time, reduces errors, and improves overall outcomes (Ma et al., 2021).

BIM and Lean Construction are both approaches that have significantly impacted the Architecture, Engineering, and Construction (AEC) industry. BIM primarily focuses on digital transformation in the construction industry, and Lean Construction focuses on improving the production management process. Studies have shown that the simultaneous application of both approaches can enhance the productivity of projects and improve efficiency (Sacks et al., 2010). It is concluded that implementing the lean-BIM approach in the design process of masonry structures will enable the introduction of non-conventional shapes, which require a smoother construction procedure on construction sites.

MASONRY UNITS

The invention of Portland cement in the early 19th century significantly altered the composition of masonry mortar. It allowed the production of concrete masonry units to replace traditional building materials like brick and stone. This invention marked a turning point in the evolution of masonry construction. Researchers state that most of the changes to masonry in the 20th century have been focused on improving production methods and refining the properties of unit masonry materials, such as making them stronger, lighter, or easier to produce, rather than introducing innovations to the masonry system itself. Such innovations can be listed in four primary groups of products and materials:

1. Masonry units and materials: the building blocks, such as bricks, stone, or concrete masonry units.
2. Masonry systems: the overall construction method, such as load-bearing masonry or cavity wall construction.
3. Mortar additives: ingredients added to mortar to enhance its properties, such as water resistance or workability.
4. Ties and reinforcement: elements such as ties or steel reinforcements provide stability and support to the masonry structure. For example, dry stack masonry units were introduced to eliminate mortar and have smoother construction. Also, Carbon fiber-reinforced plastic (CFRP) ties were brought to this industry to facilitate the reinforcement process and have multiple-wythe masonry wall (Beall, 2000).

Among all innovations introduced in masonry units, units with integrated insulations, such as InsulTech (Figure 2), have gained more attention. Such alternative masonry units can be made from various materials, and their shapes and applications are like traditional masonry units (Subasic, 2022). Constructing these units is simpler and more streamlined than conventional construction methods. However, other aspects of this unit, such as shape and structural reinforcement, are the same as traditional ones.

The main concern with the recently proposed masonry units is their compliance with thermal structural and fire safety codes. Also, according to masonry industry practitioners, the idea of having masonry blocks that do not need cement can be beneficial, as the shortage of cement supplies in Canada has indeed impacted the masonry industry, leading to a lack of masonry units and decreased productivity. Using alternative masonry blocks that do not require cement could solve this problem, allowing the industry to continue operating despite the cement shortage.

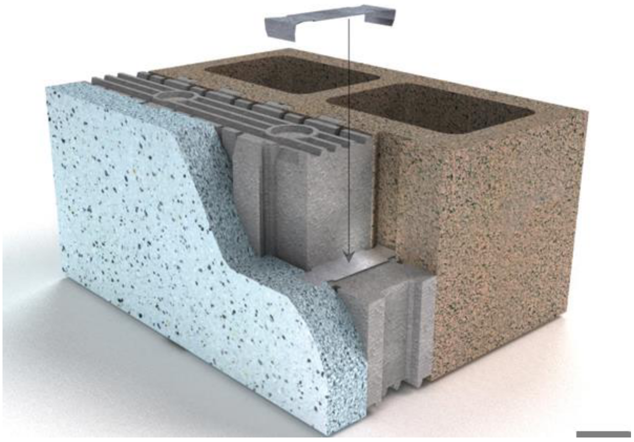

Figure 2: InsulTech masonry unit (Echelon, n.d.)

MASONRY CONSTRUCTION

Based on literature review, it was identified that waste, in all its forms, renders projects slow and vulnerable to conditions on construction sites which consequently restricts the value that can be delivered to the customer. Moreover, waste in all its forms on construction sites reduces flow and value generation (Abbasian Hosseini et al., 2012). Variability and complexity in the construction industry implement lean principles in construction processes, an attractive solution to identify Non-Value Adding (NVA) activities and subsequently improve the process. Implementing lean construction principles in the construction industry, specifically, the masonry industry has been proven to reduce waste in cycle time and efficiency. Using simulation modeling, it was concluded that more than 70% of the bricklaying activities are NVA (Abbasian-Hosseini et al., 2014). Hence, applying lean principles would make the process more efficient by reducing the time needed for NVA activities. Moreover, lean principles have been applied to the bricklaying process using Value Stream Mapping (VSM) to identify waste (Melo et al., 2017). It was determined that reducing transport times and excess inventory reduced NVA time and lead time. Another study (Bajjou & Chafi, 2021) showed that NVA constituted 85.2% of the bricklaying cycle time, with waiting (or idleness) having the most significant share. These studies applied lean principles to identify areas of waste in the masonry industry and change how bricklaying and masonry construction is done on construction sites. Hence, there is a need for more extensive use of lean in the industry. Moreover, such studies fail to include the different and more complex types of wall configurations. Current research also involves the implementation of sustainable solutions, which consists of adding robots on-site to create semi-autonomous bricklaying systems. (Usmanov et al., 2021) creates a digital layout plan for robotic bricklaying. However, such a system only considers orthogonal walls and does not consider more complex wall shapes or configurations.

The data gathered concerning masonry construction was done by multiple site visits of a school gymnasium being built entirely using CMUs as a structural element. The visits aimed to identify the difficulties encountered in masonry construction. During the visits, common types (patterns) of wall configurations using CMU blocks were identified. The goal of the visit was reached after observing the bricklayers perform their work. Therefore, the data gathered was based on the spotting and discerning of patterns of construction the bricklayers would follow. The frequency of those patterns to create different types of wall configurations and based on the current literature review, the most common types of wall configurations were found as shown in Figure 3:

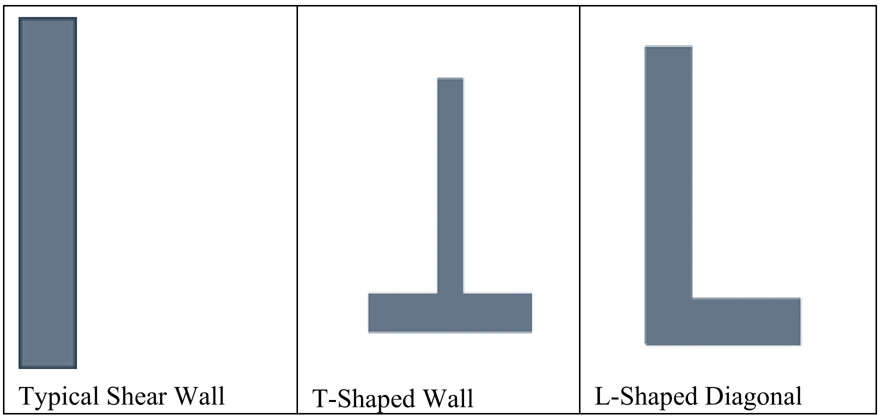

Figure 3: Most common wall configurations

Typical shear walls were found to be the most common type of masonry walls being built. Bricklaying such walls consists of several steps: lift brick, spread mortar, knock, level, and remove excess mortar. CMUs lifting leads to work-related musculoskeletal disorders (WMSDs) due to the repetitive stress of the bricklaying steps on the workers' bodies (Wang et al., 2015). The repetitive motions lead to decreased productivity over time as WMSDs disorders occur. Moreover, the current bricklaying process requires constantly refilling mortar and brick stations at the wall construction sites. The existing masonry practices are done for the different shapes of walls, but specific issues were noticed to emerge in more complex shapes (such as L and T). For L-shaped and T-shaped walls, it was observed that many problems that hinder productivity happen during construction. Most notably, the bonded wall components forming the L or T shape should be built simultaneously due to the presence of the intersection part between the two members forming the shape. Such configurations are complex to build and hence require more time to build than a typical shear wall. In addition, the variability in the geometrical design of masonry walls leads to the difficult reproducibility of such wall-shape configurations on-site. This leads to decreased productivity on construction sites. Moreover, as wall shape configurations become increasingly complex, the quantities of equipment and material needed increase. Indeed, when faced with different structural scenarios (over-opening such as lintels, change in wall thickness, etc.), there is an increase in the time required to perform the bricklaying process.

Moreover, the visits to construction sites show that the identified patterns lack productivity, with construction being highly variable, and are subject to the construction site layout planning done beforehand. Hence, there is a need for the implementation of lean concepts in masonry construction.

LEAN THINKING SOLUTIONS

Masonry construction suffers from problems in productivity and is plagued by a myriad of difficulties ranging from heavy lifting, causing a strain on the Musculo-skeletal system of bricklayers as well as non-optimal construction designs that would take more time to be built, affecting the masonry industry in both the design and construction phases. Current lean improvements in masonry systems have identified many problems impacting the bricklaying process, namely the inventory and transport issues. However, current research fails to consider a holistic integration of all parts of the bricklaying process, whether autonomous, semi-autonomous, or human-driven only, to implement lean solutions and reduce waste.

Based on the findings in the literature and after the multiple on-site visits, we present the opportunities from a lean perspective in this section. Opportunities in masonry construction (Figure 4) focus on bricklaying itself in masonry construction. Applying lean to masonry construction can increase site productivity while reducing the efforts needed for current bricklaying practices. Moreover, using lean methods would enable faster design and construction processes to deliver better value to the customer.

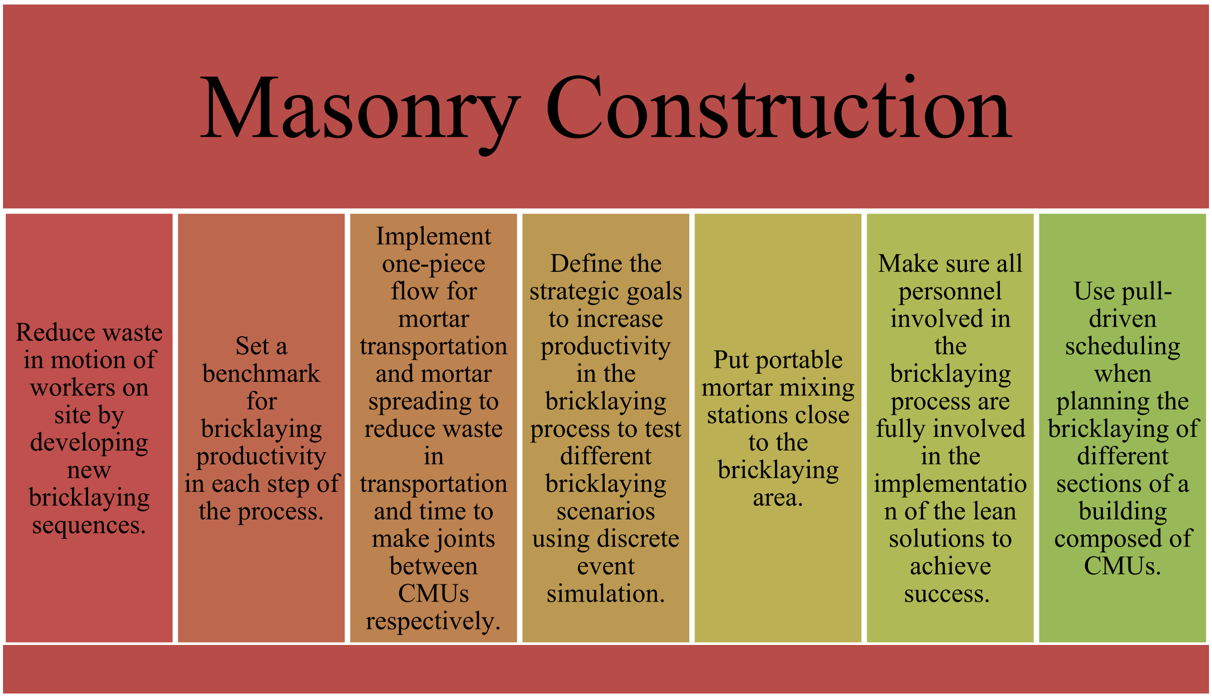

Figure 4: Opportunities in Masonry Construction

Figure 5 shows the wasted opportunities that can be applied in masonry design. Using lean practices in masonry design makes it possible to develop optimal designs in the pre-construction stages of projects. Based on the observations from site visits, having knowledgeable designers on the construction process and labor intensity of different wall configurations can help a smoother construction process. Also, according to discussions with various masonry industry experts, integrating advanced tools with a holistic masonry design approach is missing in current design practice. Here, we present some lean solutions to such problems in masonry design.

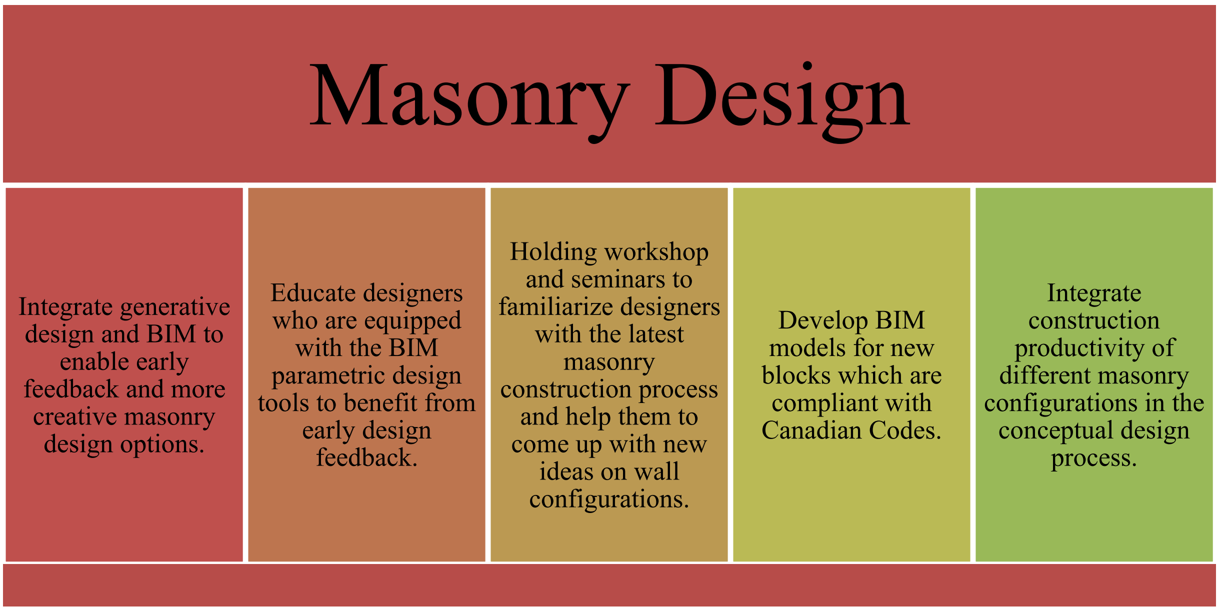

Figure 5: Opportunities in Masonry Design

Lean opportunities can also be applied to masonry blocks by creating blocks with more sustainable materials and better block shapes and designs. Figure 6 shows the lean solutions applied to masonry units:

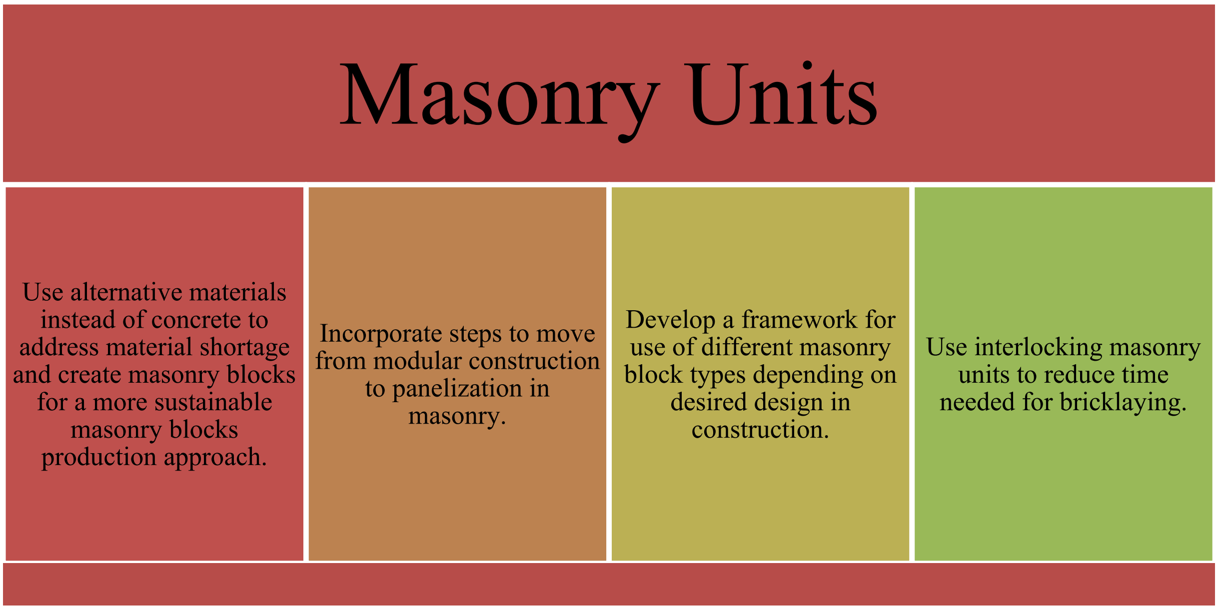

Figure 6: Lean opportunities for masonry units

CONCLUSIONS

Based on the literature review, multiple construction site visits, and discussions with industry practitioners, it has been found that the implementation of lean principles in the masonry industry can reduce waste and improve efficiency. Value Stream Mapping (VSM) and simulation modeling have shown that many bricklaying activities are non-value adding (NVA), with the largest share being waiting. However, current research focuses on orthogonal walls and lacks consideration of more complex wall configurations. L and T-shaped walls are one of the complex shapes that need to be taken into consideration when trying to improve the masonry construction process. Therefore, there is a need for more extensive use of lean principles in the masonry industry. The lack of early feedback during the conceptual design stage can lead to design fixation in masonry design, resulting in architects choosing more straightforward, more conventional solutions instead of more innovative ones. BIM is expected to revolutionize the construction industry by enabling generative design solutions, allowing for exploring a more comprehensive range of design alternatives and improving the design and construction processes. Integrating generative design and BIM can lead to a more efficient and effective design process. At the same time, the simultaneous application of BIM and Lean Construction can enhance the productivity and efficiency of projects. Implementing a lean-BIM approach in masonry design will allow for the creation of non-conventional shapes and a smoother construction process. Future research is needed to validate the effectiveness of proposed lean solutions in improving masonry design and construction. To validate the proposed methods in masonry design, intelligent BIM models can be built to benefit from generative design tools and algorithms in reaching an optimized wall layout design. In construction, we can validate our solutions using Discrete Event Simulation as they allow us to check the effect the implementations have on construction productivity and refine the models and solutions as results of the simulations become available. Moreover, the use of lean principles should not only be limited to orthogonal walls but also to non-orthogonal walls too and a study for finding the root causes of disappearing construction material in Canada should also be further investigated. Recommendations proposed for masonry block improvements can be validated by incorporating new block characteristics and geometry into the intelligent BIM model and masonry construction simulation model.

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DIGITAL SHOPFLOOR MANAGEMENT IN CONSTRUCTION – A CASE STUDY

Darius P. Heller[1]

ABSTRACT

Lean Management is considered a very promising approach to improving productivity in the construction industry. Shopfloor Management (SFM) is receiving increasing attention in theory and practice, as it has an impact on daily routines of all organizational levels. This paper presents over two years of experience in adopting and implementing SFM at a general contractor, which focuses on industrial and custom new buildings. The underlying company is following a clear and organizationally manifested approach toward Lean Management since the mid-2000s. Hence, the SFM methodology needed to be embedded in the already existing methods conceptually, before it could be rolled out. After two years of implementation, rollout to over 80 projects with an equivalent of approx. 1 billion € volume was achieved. Also, a consistent cascade from the construction site to top management was established, i.e. all levels of the organization have transitioned to the new way of working (and leading) inherent to SFM. In parallel, under the application of a strictly agile approach, the SFM cascade was digitized with a special focus on data reuse and integration of systems to ensure consistency, accuracy, and up-to-date information. The overall impact of SFM in the company underlying this case study to date is positive, and an initial approach is proposed to measure the impact in this paper.

KEYWORDS

Lean construction, collaboration, benefits realization, shopfloor management, digitization.

INTRODUCTION

The company underlying this case study is a general contractor with a regional footprint and with the majority of projects creating new buildings for non-residential usage. Some of its ten business units attempt to gain efficiencies through reuse, but the majority of buildings are customer-specific and produced on-site (no prefabrication) by subcontractors. Lean Management is being implemented since the mid-2000s when a dedicated team was created to drive and support the lean journey.

The main goals of implementing Lean Construction (strategically) in this case can be described from company, project, and people perspectives:

- *Company* - establish a culture of continuous improvement based on standards and project-overarching build-up of best-practice knowledge, leading to an increase in revenue and margin through productivity gains.
- *Project* - achieve project objectives as committed to customers (e.g. completion date), and reduce the lead time of projects to improve competitiveness.
- *People* - achieve a sustainable, motivating, and performing work environment.

The company sees itself to be a pioneer regarding Lean Management implementation in the construction industry, but as described in the problem statement later in this paper, the impact

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of Lean Management remained behind expectations. Hence, the company analyzed other enterprises outside the construction industry for further inspiration on Lean Management and discovered the concept of SFM. Starting in 2018, a team continued to investigate SFM and received the mandate to adapt and implement SFM. In this paper, a full view of the adaptation, implementation, and impact review of SFM is presented. The author acknowledges, that various other general contractors are also implementing SFM, and hopes that those companies might contribute to this research as well based on their experience.

LITERATURE REVIEW

The term shopfloor management (SFM) as it is used in this paper refers to a broader methodological approach that builds on the understanding of lean leadership as described by Liker & Convis (2012) or Suzaki (1993), as opposed to a narrower understanding of operational techniques and mechanisms to plan and control production activities (e.g. production scheduling, shift capacity planning). The word shopfloor itself refers to a focus on the teams that work mostly in direct production (Grütter et al, 2002). Bertagnolli (2018) further defines SFM to consist of the four structural elements communication, visualization of key performance indicators (KPIs), problem-solving, and process control. Hertle et al. (2017) describe SFM as a procedural model. The structural and procedural definitions align with the understanding used in this paper. Beyond literature from within the lean management domain, it is important to review publications from adjacent domains such as operations management. Dombrowski et al. (2018) present case studies in which work team performance has been improved by concepts similar to SFM. Also, less associated with the domain of lean management, but rather performance management is the article by De Leeuw & Berg (2011). In it, the effect of SFM-like interventions on productivity and motivation has been investigated. A survey of approximately 100 companies from various industries and sizes created the insight that 71% of respondents confirm productivity gains from introducing a performance management system. Regarding the digitization of SFM in general, an overview of publications is provided by Jelínková & Prochazkova (2023), showing a strong increase between 2015 and 2020. Meißner et al. (2020) developed a target state for digital SFM (not construction-specific), defining what improvements should result from digitization in the categories of identification of deviations, shopfloor meetings, problem-solving, as well as standardization and stabilization. Publications on SFM adaptation to construction reach back to 2010 (Hofacker et al., 2010), with a pure focus on the production process on-site. Lootz (2018) describes the application of SFM to a ship-building context, integrating more processes (e.g. engineering) and also covering all levels of the organization (i.e. an SFM cascade). Romano (2022) describes the practical experience of the implementation of a digitized version of SFM in a large construction company. Binniger, M & Wolfbeiß, O. (2018) present specific implementation experience from a construction company in Germany using a special pen to digitize information.

Based on the literature review in total, the author believes SFM is a necessary element on any lean journey, and that the method should not only be seen as a set of KPI boards, but as a shift towards lean leadership with the corresponding behaviors and values.

PROBLEM STATEMENT & SOLUTION CONCEPT

After a brief outline of the problem statement, differentiated into the three perspectives *company*, *project*, and *people*, the approach to SFM as a solution will be explained in detail.

PROBLEM STATEMENT

From a *company perspective*, revenue was increasing slightly year-over-year, but the margin was stagnating at a market average level for multiple years. A key problem was that losses from a few projects led to a significant negative impact on the margin of all projects and thus on the entire company over several years. Management usually received information about negative deviations in projects at a time when there was no more possibility to influence the impact. Also, comparing business units showed strong deviations in the stability of both revenue and margin, even though the business models were identical (only differing by region).

At the same time, from a *project perspective*, the company was lacking quantification of project performance in a holistic sense. The financial outcome was available as a metric, but timeliness, quality, or customer satisfaction were not quantified.

From a *people perspective*, individuals invested considerable time in meetings and reporting to ensure information flow to (a) subcontractors, (b) within the project team, and (c) to higher management levels. Typically, the time consumed to communicate and coordinate was so high, that other required processes were not feasible with the team's capacity. For example, preventive quality assurance was either not existent or executed at a minimum in most projects. In general, for all management roles, it was not possible to receive a holistic view with up-to-date and actionable items within the roles' range of responsibilities. A management role (e.g. project leader, business unit head) had to first compile information from various sources (e.g. Customer Relationship Management system, financial controlling, procurement systems, systems to manage drawings, comparing milestone schedules with Last-Planner, etc.). This information was then used to conduct meetings, in order to create a full picture through a time-consuming dialogue. Often, by the time conclusions were made, the situation was outdated. In the best case the problem was resolved, in the worst-case the problem could not be mitigated anymore and/or has become worse.

Summarizing the problem statement, the company's general management approach can be described as lagging, and there was a chronic state of unsatisfying information even though time invested in information processing and communication was significant.

SOLUTION CONCEPT

The SFM methodology was selected as a solution concept because it seemed to address many aspects of the problem statement and at the same time was consistent with the company's overall goals of implementing Lean. SFM would replace traditional ways of communication and reporting with a short-cyclic, dialogue- and metric-oriented, standardized management routine which was claimed to be very efficient by strongly increasing the relevance of and reducing time spent on communication on all levels of the organization simultaneously (Bertagnolli, 2018). This effect has been recently also confirmed by research (Wester & Hitka, 2022), based on an SFM implementation in a company in Germany (steel industry).

In total, it was expected that SFM would reduce the negative impact of loss projects from a company perspective, help achieve committed goals from a project perspective, and at the same time free up time and reduce stress by decreasing interruptions from a people's perspective. The key elements of the solution concept are as follows:

- Stand-ups with a weekly cadence were defined internally on all levels of the organization to form a SFM cascade (like on page 359 in Fiedler, 2019). Stand-ups with contractors (on-site) were executed daily. The structure of stand-ups is displayed in table 1. The stand-ups were executed in person, hybrid, or virtually.
- The duration of the stand-ups was planned to be 15-20 minutes, focusing the dialogue on the main issues and not attempting to solve them during the stand-ups.
- The contents of the stand-ups were structured in advance by means of SFM boards with topics and KPIs. An overview of the contents is given in tables 2 and 3.
- The SFM boards were defined for four roles initially: on-site leader, project leader, business area leader, and managing director. In this paper, the focus will be on the boards for on-site and project leaders, as these are most relevant to the shopfloor.

In case deviations on the SFM boards of the on-site and project leaders exceeded a predefined threshold, the issue was escalated to the next level. A choice could be made if the escalation is informative, or required action by the higher management level.

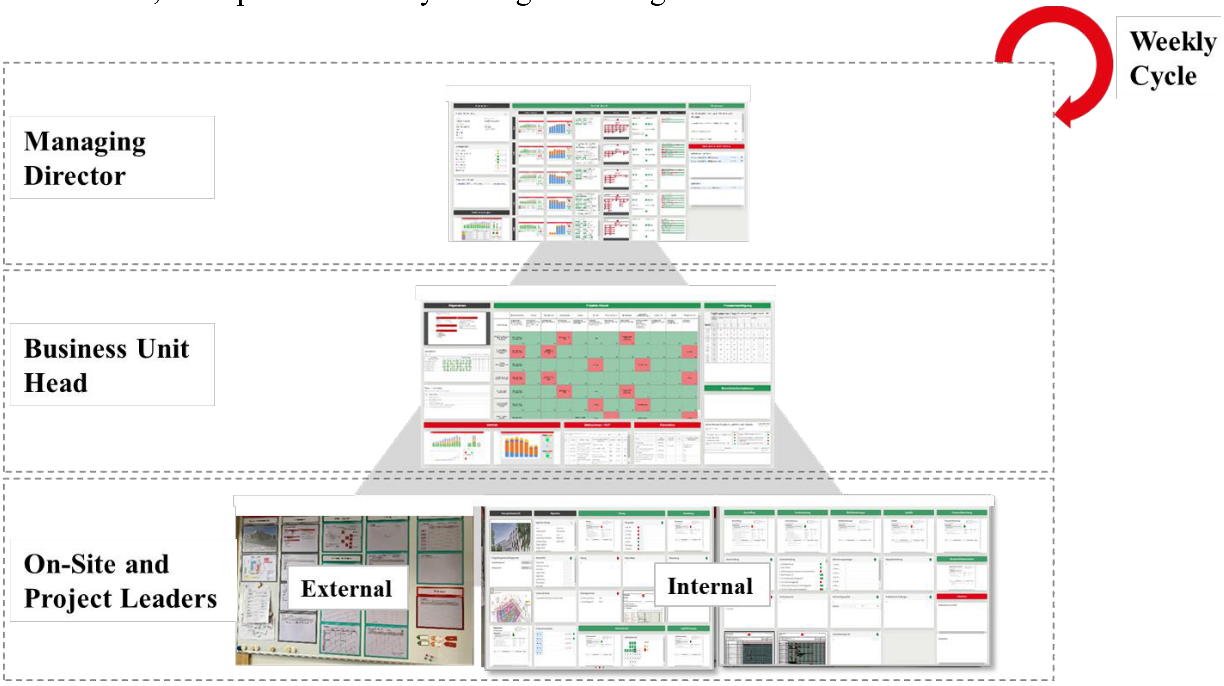

Figure 1: SFM Cascade

The following table shows how the stand-ups were synchronized to ensure up-to-date information throughout the organization. Conceptually, a cascade fully synchronized on a single day would have maximized the timeliness of information, but due to central functions that participate in multiple stand-ups on the project level (especially procurement), a second day was also required for project-level stand-ups.

Table 1: Schedule for SFM Stand-Ups

Stand-up type	Weekday		
	Mon-Wed	Thursday	Friday
Internal	no stand-ups	any time: project leaders	08:00-10:00: project leaders 10:00-11:00: business unit heads 11:00-12:00: managing directors
External	on-site leaders: preferably in the early morning (daily)		

From the view of a project leader, the 15-20-minute stand-up can be executed on Thursday, or Friday before 10:00. Between 10:00-11:00, all project leaders participate in the stand-up of their respective business unit head which is expected to take up to one hour (some business units have 15 projects running in parallel, others 5). Consecutively the business units' heads participate in the stand-up of their managing director. Also, the duration can be up to 1 hour depending on the number of business unit heads per managing director. It is conceptually clear that not only the proportion of organizational units (e.g. number of projects per business unit head) is a driver for the duration of stand-ups, but also the number and severity of issues, as well as the communication behavior of the participants.

The contents on both SFM boards can be distinguished into actual KPIs versus topics that are a useful basis for communication. This is not strictly in line with SFM theory but was thought sufficient to still achieve the desired impact by posting topics on a board that regularly are the cause of phone calls or multiple emails per day.

The following tables 2 and 3 depict the KPIs / topics which were used for the on-site and project leaders. Each line item was a sheet of paper (or later a digital tile) on the SFM boards.

Table 2: Contents of SFM Board for on-site leaders

No.	Title	KPI / topic
1	Health & Safety	# days since the last incident
2	Logistics (1)	One-week calendar to enter planned events (e.g. use of crane)
3	Logistics (2)	List of materials to be supplied by general contractor
4	Planning	List of plans and their revision for the current week
5	Production	# of people on-site planned vs. actual and deviation per trade
6	Quality	Rework overdue by more than one day
7	KAIZEN	Lessons learned for continuous improvement
8	Actions & escalations	List of actions and escalations if a threshold is exceeded

The SFM board for on-site leaders was typically located in a container accessible to contractors. As mentioned above, daily stand-ups were executed in the morning to assess each of the KPIs / topics.

Table 3: Contents of SFM Board for project leaders

No.	Title	KPI / topic
1	Health & Safety	# days since the last incident
2	Sampling	Overdue sampling
3	Planning (1)	Risks identified per planning partner
4	Planning (2)	Overdue drawings
5	Planning (3)	Evaluation of performance per planning partner
6	Tender (1)	Requests for proposals overdue
7	Tender (2)	Contracts pending overdue or over budget
8	Production	Milestone status (planned vs. expected / actual date)
9	Quality	Status of preventive quality plans per trade
10	KAIZEN	Lessons learned for continuous improvement
11	Actions & escalations	List of actions and escalations resulting from deviations
12	Process Map	List of work packages and their status

The SFM Board for project leaders was initially located either in a container on-site or in the office of the project leader. The location of the SFM board for project leaders was an issue, because project leaders typically worked both from the construction site, but also from the office. The participants of the stand-ups were also split into those that worked on-site, and those that worked from the office (e.g. procurement).

OVERALL LEAN CONCEPT WITH SFM

SFM needed to be integrated into the existing Lean concept, which has evolved since the mid-2000s. For this purpose, a short overview of the existing Lean concept is given in table 4.

Table 4: Levels of existing Lean concept

Level	Main elements of the Lean concept
Company	• Retrospective after each project (approx. ½ day in the project team) • In-depth analysis of loss projects • Idea Management
Project	• Process Map • Project Team-Meeting (discontinued with SFM) • Project Reporting (discontinued with SFM)
On-site	• Last-Planner-System • Logistics (in- and out-bound) • Quality (preventive and reactive)

The first level, *company*, is a level that is often missing from the author's view when implementing Lean Construction. Its objective is to manifest and accelerate a learning curve across the entire company and project portfolio. To achieve this objective, the approach is to make ways of working transparent and to exchange lessons learned in a systematic way. It was expected that SFM supports this level because the recurring process of exchanging lessons learned was integrated into SFM.

The second level, the *project*, was implemented by means of a standardized Process Map, which contains a work breakdown structure in combination with quality gates. The Process Map is digitally provided to the teams quoting or executing a project as a guideline to complete the required work. Each work package is scheduled and executed by the responsible person in the team. The completion is tracked in the digital tool and aggregated to the project leaders. In regular intervals of two weeks, the project team and the leadership met to review the progress of the work packages. After the review, a one-page report containing KPI and potential escalations was created by the team, which was intended for review by higher management.

SFM conceptually overlaps with the second level in three areas. (1) the weekly stand-up and the bi-monthly team meeting. (2) the use of KPI, and (3) the function to escalate. It was decided to replace the bi-monthly team meeting with the weekly stand-up, reducing the planned time spent on this process from 4 hours per month to 2 hours per month. To keep track of the work package progress in the Process Map, information on the degree of completion of work packages was included in the SFM board of the project leader (automatically generated). The report containing KPI was also replaced by the SFM boards. With SFM, a more sophisticated set of KPIs was defined by differentiating by organization level (previously not the case). Potentially the most impactful decision concerning (3) was to replace the existing reporting with stand-up meetings also for higher management (i.e. cascade) and to define thresholds for each KPI and organizational level.

The third level, *on-site*, was based on the Last-Planner-System with the corresponding tools and meeting structure. According to Hofacker et al. (2010), SFM conceptually is an addition to the Last-Planner-System by providing a daily routine with multiple topics relevant to short-term production management (e.g. materials required, staff on site). It was intended that communication otherwise happening during the day and leading to interruptions would be combined in the daily stand-up, creating an efficiency gain and leading to smoother communication patterns.

The following picture illustrates the three levels with the main elements relevant to SFM:

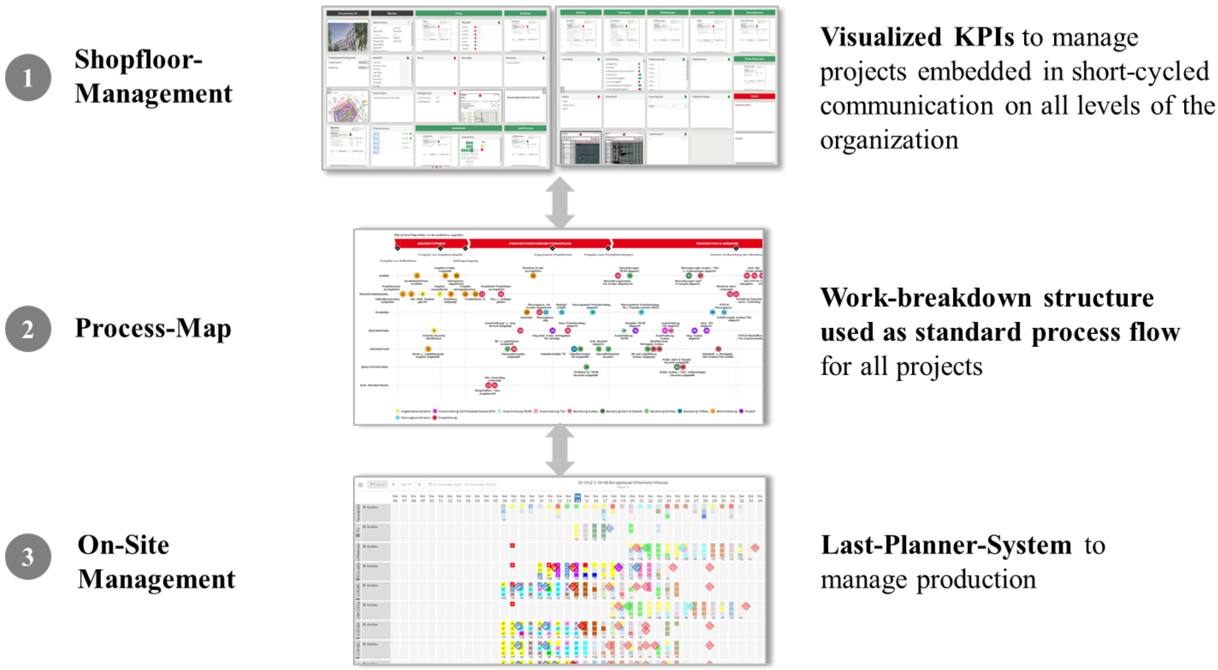

Figure 2: Extract of Lean concept relevant to SFM

IMPLEMENTATION APPROACH

After an explanation of the general approach to introduce SFM, the digitization approach is elaborated in more detail due to its high relevance from the view of the author.

General Implementation Approach

With regard to change management, the planned approach was to proceed in four steps:

1. *Conceptualize* with stakeholders from two of ten business units, and thereof representatives of all organizational levels. The stakeholders started with external benchmark visits before conducting internal workshops.
2. *Pilot and Refine* – after piloting one project from each of the two business units with the close involvement of leadership, the methodology was refined based on the outcomes and experience of the pilots.
3. *Rollout* to all new projects while applying a just-in-time training for each project team individually. In parallel, the so-called cascade for the business area leads and managing directors was built-up (equaling three conceptual levels of SFM).
4. *Review* the maturity of implementation of SFM on a per-project level regularly, make the maturity assessment transparent to the project leader, and give advice on how to improve and integrate it into regular reporting to managing directors.

A duration of two years was planned from the start of conceptualization to the start of rollout. The introduction of SFM was managed by a person with strong experience in lean management.

Digitization Approach

The company decided to implement a custom-developed digital solution following a strictly agile / SCRUM-based approach as outlined in Brenner (2019), p. 141 - 143 based on the following key principles:

- a usable version of SFM had to be available within three months, to not deviate too strongly from the overall timeline to rollout SFM to all new projects.
- the digital version had to be an identical copy of the paper-based version to reduce the complexity of two SFM versions – in terms of the contents - in parallel.
- the SFM board had to be optimized for large touch screen use, to maintain the "look and feel" of a physical SFM board.

The development teams were in a near-shore location managed by a consultant in Germany. Weekly calls were set up to prioritize scope with a fixed budget and monthly release cycles. For each of the contents on the SFM boards, three data integration steps were differentiated and implemented in an incremental approach:

(1) It is possible to access the underlying data with a maximum of one click. This was achieved by the simple linking of documents. (2) It is possible to reuse data values from other systems and display them on the SFM boards. (3) The SFM board displays the result of a computation, hence actually assisting in the interpretation of data. As an example, the system would compare the dates of actual drawing delivery (from a cloud-based platform) with the scheduled and thus expected delivery dates (in a specialized scheduling software), and deliver a key performance indicator such as weekly schedule adherence in percent.

DISCUSSION

To date, there is no literature specifically attempting to quantify the impact of SFM on the KPI of construction companies. Hence, the following measurement approach is a proposal subject to adaptation based on further research and feedback.

The business impact from a *company perspective* is considered to be lagging and a direct correlation to SFM difficult to prove. Still, an attempt was made by tracking the total (negative) earnings impact from loss projects. The measurement showed a clear reduction of this KPI, as shown in table 5. The revenue of the company was more or less the same at the two points of measurement.

With respect to the *project perspective*, an analysis of on-time completion was conducted. Measurement of on-time completion was not measured previously in the company. As a consequence, data first had to be collected and cleaned for example by analyzing causes of prolonged construction in detail: if the customer added scope to the project, the target completion date was deferred, hence the project was on-time if the deferred date was met. As table 5 shows, also a clear improvement could be observed. One must note, that this improvement might have been influenced by factors (external/internal) beyond SFM. There was no ex-ante prolongation of schedules to improve on-time completion.

From a *people perspective*, time savings in combination with better information quality were positive impacts. To explain in more detail, this perspective will be further differentiated into individual, project team, and management (business unit heads and managing directors):

For *individuals*, it was estimated that the time previously spent to process information required to fulfill one's management role (independent of level) was at least 2-5 hours per week. Example tasks are: reviewing information in systems, lists, or reports, fetching information by email or personal interaction, or conducting meetings. Because this value strongly depends on the working style and organizational performance level, it varies strongly. With SFM there is a range of 30-60 minutes per week to achieve at least the same information level. Also, SFM led to a reduction of interruptions because the stand-ups offered a structure for communication instead of the multitude of people involved in a construction project communicating with each other. This reduction of interruptions has not yet been quantified.

For *project teams,* an average of 30 minutes (vs. 15-20 minutes as expected) is required per week, hence 2 hours per month, for the project leader's stand-up compared to the previous 4 hours per month for team meetings. Only these figures from the people perspective were included in table 5, since they have less variance than the figures for individuals. Feedback was clear that the information shared during a stand-up led to a much better result in terms of all team members being synchronized. Ideas to solve problems were shared in the team much more dynamically, which is expected to benefit the project-level mid-term.

Also, *management* reflected uniformly that the quality of information (i.e. the value resulting from the time spent sharing information) was better than before. The information was more complete, up-to-date, and accurate than previously. As another clear impact, the relevance of issues communicated was higher (due to thresholds defined uniformly in the company). If the negative impact of an issue did not exceed the threshold, the team continued to solve the issue without investing time in communication with the next hierarchy level.

The impact on all levels needs further investigation. The author recommends companies aiming at introducing SFM, invest more in baseline quantification and in keeping track of the impact on a regular basis.

Table 5: Overview of indicators to evaluate impact of SFM

Perspective / Indicator	First quantification	Second quantification	Change	Hypothesis on cause-effect logic
Company sum of negative earnings from loss projects	100 points (as indexed baseline; end 2020)	37 points (mid-2022)	-63%	By recognizing deviations earlier and creating more effective solutions
Projects on-time completion of projects	100 points (as indexed baseline; 2020; n=53)	126 points (2021; n=45)	+26%	Higher awareness of schedule deviations (target / actual) compared to Last-Planner alone
People time spent in project meetings	4 hrs/month (2 x 2 hrs)	2 hrs/month (4 x 0.5 hrs)	-50%	Efficiency of stand-ups due to structured communication

With respect to the *contents* of the SFM boards, the general agreement was that all topics are relevant to successfully manage from the view of the respective role. At the same time, especially from the group of project leaders, it was noted that the SFM board contained too many elements to be handled efficiently. Also, major feedback was that the project leaders claimed to already know most of the information that was written on the SFM boards. The response to this was two-fold: (1) after multiple discussions with project leaders during refinement / continuous improvement of the SFM methodology, the outcome remained to be that all topics on the SFM boards are required for their management role. Regarding the feedback of already existing knowledge, an assessment showed that the change in communication behavior (resulting from SFM) was not fully achieved on an individual level: it is ineffective to continue the communication/information processing approach applied over years and apply SFM in parallel. The project leaders need to change the communication approach by regarding the SFM stand-up as the primary source of information, and ask the team members to provide their information not ad-hoc during the week, but instead during the stand-up (except for very time-critical issues). This change was underestimated and is a learning which may help other companies in the adoption of SFM.

The next learning concerns the *digitization* approach. The agile / SCRUM-based approach was very positive regarding flexibility and output. But the decision to implement a paper-based version on the project level before digitizing should be critically reviewed. The majority of negative feedback received was that the paper-based version was not only inefficient (writing by hand data that is available in systems and then feeding the issues over the threshold into the management cascade), but also created paper waste that can be avoided, and caused limitations to involve the full team during stand-ups. Team members concerned with the planning and procurement process could not be well integrated into a stand-up unless it was conducted in the office. This is not the intention of SFM, because the stand-up should take place on the construction site. Using a digital board allows the entire team to access it, independent of location (and time). Due to the SCRUM approach applied in software development, a usable version of the digital SFM board was available after only three months. With respect to the overall timeline of two years from the start concept to the start rollout, it is recommended to build the digitization into the timeline and start with the digital version earlier. This is contrary to the recommendation given on page 120 by Leyendecker & Pötters (2020). A relevant difference may be, that the company underlying this case study had a strong history in Lean. From an IT equipment perspective, the pilot projects showed that a very large touch-screen was not required for SFM. A regular (non-touch) screen on-site was fully sufficient to execute a stand-up. Because all sites were already equipped with a screen and a team meeting area, no additional investment was required.

In total, the expected positive effects of digitization outweighed the potential risks outlined by Clausen et al. (2020), with the exception of on-site leaders. Digitization of the boards for external stand-ups was discontinued, because on-site leaders gave feedback that the digital version was considered a too high barrier and culturally incompatible.

CONCLUSIONS

Over 2 years of implementation have created valuable experience regarding the adaptation of SFM to the construction industry. The results presented show measurable positive impact from all the perspectives (company, projects, people). Given the benefits outlined in this paper, the author expects a strong increase in SFM implementations in construction in the next years. Further research is required regarding the measurement of the impact created by SFM. The indicators presented in this paper are the first proposals, which should be further discussed. Also, it will remain a challenge to separate the causes leading to changes in such indicators aside from SFM, to isolate as much as possible the pure impact of SFM.

The paper shows that early adoption of a digital SFM system will increase acceptance and hence facilitate rollout. As the availability of technology to process large amounts of data advances, more intelligent features can be included in such a digital SFM system. This is positive and critical alike because it should be well understood that SFM is – at the core – a fundamental management approach, not just a set of boards or an IT tool showing numbers on a display. Companies seeking to embrace SFM should be aware that its successful implementation will strongly depend on the readiness to create teams that are more autonomous than in traditional hierarchical and functional setups, and that the teams are motivated to not only solve issues in the individual project but also to identify root causes of issues in the sense of company level continuous improvement and learning.

ACKNOWLEDGMENTS

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AN EXAMINATION OF IGLC TAKT LITERATURE - LEARNINGS & OPPORTUNITIES

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ABSTRACT

Takt is gaining attention in the Lean Construction (LC) community and is recognised as an enabler for continuous improvement and a more complete implementation of LC. Adopting Takt from its manufacturing roots to construction has not been straight forward. International Group for Lean Construction (IGLC) research has adapted Takt principles and practices creating several models for its application in construction.

This study is an integrative literature review of papers in the IGLC index with 'Takt' in the title. Forty-eight papers were critically analysed, and key findings were themed by content analysis.

Findings show increasing interest in Takt studies since 2012 with Finland, Germany, US, and Norway respectively producing most papers. Takt has evolved from early application of Toyota Production System concepts and, with the addition of production and LC theory, has developed towards a more complete production planning and control framework with the potential to stabilise construction inputs, outputs, customer value, and quality. Takt research is beginning to impact project delivery with positive results witnessed as well as numerous challenges and improvement opportunities being identified. It is now recognised as a viable and proven production system that can initiate systemic improvement in construction delivery.

The research suggests every project should consider Takt from the outset in its high-level strategic planning and continue to assess where several sub Takt-plans can contribute to the execution of the project, assisted by LPS and the broader suite of LC techniques.

KEYWORDS

Lean construction, Takt planning, Last Planner® System, continuous improvement.

INTRODUCTION & LITERATURE REVIEW

Construction project management has predominantly relied on the Critical Path Methodology (CPM) for over 60 years, but its traditional use has been critiqued for failing to address the needs of production management (Ballard and Tommelein, 2021). Over-running tasks, in addition to scheduled tasks being 'forced' to commence because they have been committed by the CPM schedule, cause excessive and unnecessary work-in-progress and knock-on coordination, safety, quality, cost, and people related issues on projects. Academics and

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practitioners alike have debated the shortfalls of CPM and have suggested alternative methodologies (Lean, Last Planner® System, Agile, Scrum, Takt) for the management of project controls, scheduling, planning, and execution. Recent years has seen an academic-led advancement of Takt planning studies in LC. Researchers Seppänen, Lehtovaara, Koskela, Ballard, Tommelein, Frandson, Drevland, Dlouhy, Schöttle, Nesensohn, Binninger, and Haghsheno have led and advanced application methodologies for utilising Takt concepts to enhance construction planning and production management. These studies illustrate how construction can incorporate Takt time as a work structuring methodology to align the production rates of trades by pacing work sequentially through planned zones creating continuous workflow, reliable handoffs, and an opportunity to continuously improve the production system (Frandson et al., 2013). Takt time regards 'space' as a resource to be considered when planning construction projects and designing production operations (Frandson et al., 2015).

TAKT PLANNING

The word 'Takt' or 'Taktzeit' in German means 'beat', 'rhythm', 'cadence' or 'meter', implying the regularity with which something gets done. In the production context, Hopp and Spearman, (2011) defined Takt time as: '…the unit of time within which a product must be produced (supply rate) in order to match the rate at which that product is needed (demand rate)'. It is a design parameter used in production settings that asserts if a process proceeds too quickly it will overproduce, and if it goes slower there will be a bottleneck (Frandson et al. 2013). Another critical consideration is that in construction workers move around the work as opposed to the work moving to the worker, for example, through a manufacturing assembly line (Ballard and Howell, 1997). Frandson et al. (2013) suggests the difference between Takt time planning and other location-based planning methods is this balance between 'work waiting on workers' and 'workers waiting on work.'

Takt time is easiest to understand in a machine-paced flow line, where each workstation along the assembly line must complete its work during the time the product is in its work zone. If the necessary work is not completed, the product proceeds to the next workstation in an incomplete state causing disruption to operations flow (Frandson, 2019). To minimise worker movement, work zones are kept as small as possible, with consideration given to the speed of the line and the capability of each workstation (Hopp and Spearman, 2011). By addressing process flow instead of solely maximising labour efficiency, Takt production accommodates the development of overall flow, especially when strategic buffer management occurs in contrast to the traditional use of large time and space buffers (Lehtovaara et al., 2021).

Several approaches to Takt implementation in construction have emerged from the literature. Takt Planning and Takt Control (TPTC) is highly structured and top down oriented (Dlouhy et al. 2018) and demarcates areas and repeatable 'Standard Space Units' (SSU) for each different function (such as an office). Work packages are then developed, and assignment metrics are calculated to assess the work content per work package. Takt areas then become combinations of SSUs (Binninger et al., 2017).

Allowing the trades involvement and consideration of the work sequence is a more bottom-up approach incorporated in Takt Time Planning (TTP) (Frandson et al. 2013); securing promises and social commitments speaks more to a softer collaborative environment. Focusing on maximising the amount of production activities performed with continuous use of resources is a critical element of TTP. This is possible by applying LPDS and TPS principles, and by taking advantage of the environment LPS provides (Frandson et al., 2014). TTP evolved by considering the use of 'space' and accommodating capacity buffers by scheduling less work than required to allow for variation (Tommelein, 2017).

'Work Density' is expressed in unit of time per unit of area and can be defined as: *Given a certain work area, work density describes how much time a given trade will require to do their work in that area, based on the product design and the scope of work done by that trade for a given task in the schedule (thus depending on the work already in place and work that will follow), the means and methods the trade will use to do their work while accounting for their crew's capabilities and crew size*, (Tommelein, 2017).

Takt production visualises the construction process in a way that includes work packages, work sequences, and Takt areas (Haghsheno et al., 2016; Dlouhy et al., 2016). Construction can utilise Takt time as a work structuring methodology to align the production rates of trades by pacing work sequentially through planned zones creating continuous workflow, reliable handoffs, and an opportunity to continuously improve the production system; Takt time is a design parameter for labour-paced flow of work (Frandson et al., 2013). Frandson et al. (2014) posits the objective of Takt time planning is to help create a more stable environment for the LPS by actively designing continuous workflow for trade activities wherever possible. LPS then provides the control mechanism and stability of the production system.

RESEARCH METHODOLOGY

RESEARCH OBJECTIVE & QUESTIONS

The paper reports on a review of only IGLC literature related to Takt planning. The primary objective is an examination of how Takt planning research has evolved and developed through the work of the IGLC academic community and how Takt is being interpreted and developed for use in construction. This will be achieved by answering several research questions. LC originated in the early 1990's with Ballard, Howell and Koskela's work in developing LC theory and LPS. Over subsequent years a growing body of knowledge has seen the development of specific tools for LC as well as the adoption of methodologies from other sectors. The first research question asks: What are the learning opportunities from the timeline and geographical spread of LC Takt publications? The second asks: How has LC Takt planning evolved over time? and the third question asks: What are the challenges/risks when implementing LC Takt planning?

METHODOLOGY

The methodology to identifying and evaluating relevant Lean literature consists of an integrative literature review (Snyder, 2019) of IGLC research publications (available at: https://www.iglc.net/papers). Figure 1 presents the methodology utilised.

Figure 1: Integrative literature review methodology utilised.

In accordance with best practice described by Snyder (2019), the integrative literature review containing the keyword "Takt" in the title searched the entire IGLC database from years 1996 to 2022 inclusive. This search yielded 84 results. These were read, and some were discounted due to lack of relevance and for clarity the search was narrowed to only those papers with "Takt" in the title, reducing the selection to 48 IGLC conference papers. Each paper was critically analysed, and emerging themes were evaluated by content analysis in accordance with Creswell and Poth (2016). Findings were collated and key themes are discussed.

LIMITATIONS

The study is restricted to IGLC literature with the word 'Takt' in the paper title. The authors acknowledge there are numerous studies within the IGLC index that refer to and contribute to the development of the construction Takt body of knowledge. Additionally, there are several publications available outside of IGLC that have not been considered in this study.

FINDINGS AND DISCUSSION

RESEARCH QUESTION #1. WHAT ARE THE LEARNING OPPORTUNITIES FROM THE TIMELINE AND GEOGRAPHICAL SPREAD OF LC TAKT PUBLICATIONS?

Examination of the timeline of IGLC publications with 'Takt' specifically in the title highlights no publication before the 2012 conference. The initial paper in 2012 (Fiallo and Howell, 2012) was followed with papers at every subsequent conference, the peak being nine studies in 2019. Figure 2 presents the number of studies per year.

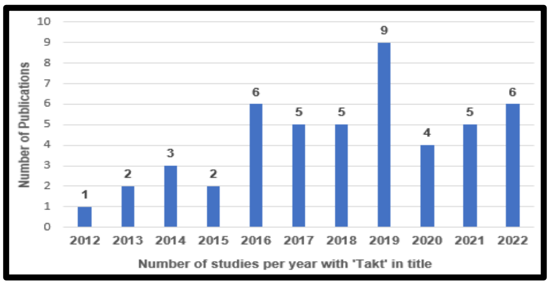

Figure 2: Number of studies.

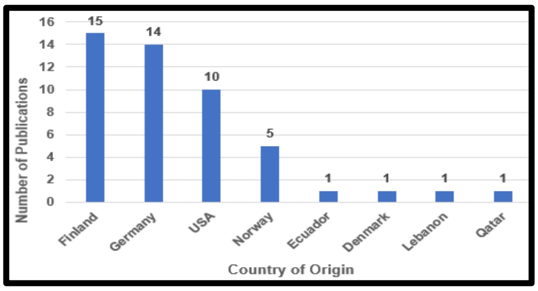

Figure 3: Geographical distribution.

The geographical distribution of studies is spread across eight different countries (Figure 3) with Finland and Germany leading the way with 29 out of 48 (representing 60% of the selected sample). Interestingly, the 2012 paper was a case study on an Ecuadorian project with Ripconciv Contractor and the lead author was both a Professor of Civil Engineering and a Lean Construction Coordinator with the case company. The co-author, the late Greg Howell, was President of the Lean Construction Institute. There has been an increasing focus on Takt planning research primarily driven by academic institutions in Karlshrue Institute of Technology, Aalto University, Norwegian University of Science and Technology, and UC Berkeley. Industry support has primarily come from the Boldt company, Sutter Health, BMW AG, Fira Oy, Skanska Oy, Consto, Veidekke, and Civil Soft Ltd. The research methodologies utilised are dominated by case studies with 35 of the 48 papers examined (73%) using this method.

RESEARCH QUESTION #2. HOW HAS LC TAKT PLANNING EVOLVED OVER TIME?

While the first paper with Takt in its title didn't appear in IGLC until 2012, it is important to acknowledge that earlier contributions identify the importance of Takt concepts and how they could assist construction planning, for example, Bulhões et al. (2005). Takt concepts (value generation, customer focus, demand rate, throughput, production rate, bottlenecks, value stream mapping) were introduced from the Toyota Production System (TPS) onto construction planning on a case project (Fiallo and Howell, 2012) and highlighted the effectiveness of Takt time as a communication tool for translating project goals to production daily goals. Significant schedule reduction (11 months to 5.5 months) on an exterior cladding installation was presented by Frandson et al. (2013) by developing a production schedule with a 4-day Takt time. This study offered a distinct process of six phases for identifying a Takt time to be used in production planning and was based on repetitive activities on the case site. At the same time Linnik et al. (2013) experimented in Takt application to non-repetitive work (interior framing phase) on a

Sutter Health hospital project. The study concluded that Takt planning does not require segregation of repetitive and non-repetitive areas and its application enhanced labour productivity through simplification and transparency of workflow and the drive for improved design of operations.

Also on the non-repetitive application theme, Tommelein (2017) reported on the 'work-density method' which proposed formalisation of a five-step process for collaborative Takt planning of non-repetitive work. Several papers bridged the gap from both LPS and Location-based planning to Takt planning and helped practitioners understand how they could transition towards keeping work flowing continuously (Frandson et al., 2014; Seppänen, 2014; Frandson et al., 2015; Schöttle and Nesensohn, 2019). Many studies (Faloughi et al., 2015; Emdanat et al., 2016; Heinonen and Seppänen, 2016; Vatne and Dreveland, 2016; Frandson and Tommelein, 2016) advanced knowledge by applying Takt concepts on individual case projects. However, the authors assert three critical bodies of work have contributed to the advancement of Takt planning knowledge; the work of Professor Haghsheno and the researcher teams from Karlsruhe Institute of Technology; Professor Tommelein and the researcher teams from UC Berkeley; and Professor Seppänen and the research teams from Aalto University. Despite having a lesser quantity of papers at IGLC the contributions from Norway and the individual cases from Denmark, Ecuador, Lebanon, and Qatar have contributed positively and enhanced the body of knowledge.

Haghsheno et al. (2016) took the approach of controlling takted construction processes by agreeing that ideal process analysis and the standard room units preceded determining the effort levels required for each activity. The goal is to level out the work packages ensuring the single unit of Takt time is not exceeded. Attention is focused on the detailed analysis and integration of customer demand, space, crew size, output, and buffer allocation to achieve stable construction processes. Key to this study's success was the focus on shorter cycle Takt time and quality completion of tasks. An interesting difference in approach is Frandson et al. (2013)'s use of a four-day Takt time, and Frandson and Tommelein (2016)'s use of a five-day Takt time as opposed to the Karlsruhe researchers who preferred to get as close as possible to a short-cycle or single day Takt. An exception to this is Dlouhy et al. (2016) who filled 'wagons' to achieve a five-day Takt time to level with longer duration activities. Binninger et al. (2017) used two and half day Takt on the first floor and five-day Takt on the ground floor of the case project. When Dlouhy et al. (2018, p.892) examined 10 construction case studies they found an average Takt time of 4.4 days and add '…Takt Time can have duration from a few minutes up to one week.' Studies show that in construction projects the Takt time generally lies between half a day and one week. This study asserts an opportunity exists for researchers to collaborate and agree the ideal process and approach towards establishing Takt time for the wide variety of scenarios that exist in construction and along its supply chain.

When reporting on the case of combining Takt with prefabrication, Chauhan et al. (2018) aggressively sought a one-day Takt time and again highlighted success by combining multiple Lean concepts. In a seven-story apartment project, Lehtovaara et al. (2019) combined a one-day and five-day Takt when interior finishing 42 apartments of varying layouts and floor areas. In summary of this point, Binninger et al. (2018) analysed 80 construction projects where Takt planning was used and found approximately 75% used a Takt time of one week. In contrast, an example of Heinonen and Seppänen (2016) describes a Takt time of 15 minutes which presented excellent improvements in cruise ship cabin refurbishment and posed the challenge to construction that improvement goals set in construction have been too low, possibly due to lack of external pressure or demand. Binninger et al. (2017) conclude that every project could have a different Takt time while noting that in practice a weekly Takt is often selected due to the instability of construction processes.

The contributions presented in table 1 assess the emerging themes from 41 of the 48 analysed papers that have emanated from four research institutes. Table 1 highlights the broad range of technical, tactical, cultural, and softer aspects to be considered in Takt implementation. Interestingly, recent years has seen more interchange of ideas and views with collaborative studies presented, for example, Lehtovaara et al. (2022).

Table 1: Principal research contributions (41 of 48 papers)

Authors	Content focus & contribution
Haghsheno & Karlsruhe researchers	Shortest possible Takt time – measuring tasks in decimal minutes, one-hour Takt time tested, single day is recommended; quality completion of tasks; Introduced three levels – Process Analysis, Takt Planning, Takt Controlling. Takt Planning and Takt Control Method (TPTC); Case studies in automotive sector construction projects (BMW); Takt learning simulation game; Use of Takt in equipment installation; Introduced flexibility - decoupling of Takt area, empty buffer wagons, phase interlinking, soft start, and train stoppage; Takt applied on large scale project; introduced double packaging and sequencing; comparing construction and equipment phase Takt planning; Focus on buffer management; Takt workflow.
Tommelein & UC Berkeley researchers	Six sequential phases of Takt planning process; Takt Time Planning Method (TTP); Determine Takt time by overall duration allowed or consider available resources, identify bottleneck, improved bottleneck becomes demand rate. Case studies primarily in Sutter Health projects. Four- or five-day Takt time. Introduced 'Work Density Method' to find repetition in non-repetitive work. Formulated five steps for collaborative Takt time planning; Visual digital tools; Takting the Parade of Trades Model; applying Failure Mode & Effects Analysis (FMEA) to control Takt;
Seppänen & Aalto researchers	Linked existing research on location-based techniques to Takt for construction; Cruise ship refurbishment showed huge benefits terms of quality, productivity, work-in-progress and cycle time and highlighted Takt potential; combining Takt and pre-fabrication; focus on short Takt times (15 minutes – cruise ship, one day on prefabrication); Discussed impact of logistics and external variation; compared US (Californian) and Finnish approaches and maturity level; Model describing Takt maturity; Takt in renovation project; Client's perspective on value-creation and flow; Introduced visual management and digital technology as part of Takt Control; Continuous improvement system; applying FMEA to control Takt.
Drevland, Lædre, Andersen & Norwegian University of Science and Technology researchers (NUST)	Proposed aligning salary / payment terms to facilitate Takt; consideration of Takt overhead costs; suggest development of guidelines for consistent Takt implementation; considers early division of the project into many smaller phases and postpone the details until the individual phase is to be performed; highlight impact of delays in disrupting Takt.

Four specifically different approaches become evident from analysis of the studies. A synopsis of the steps in each approach is presented in table 2.

Two alternatives to define the overall Takt time are suggested by Frandson et al. (2013). The first is based on the duration to complete work and the second is to consider available resources, identify the bottleneck, study if the bottleneck's rate can be improved, and use the improved rate as the achievable demand rate (Heinonen and Seppänen, 2016). Setting the Takt time in Heinonen and Seppänen's (2016) study was a mathematical exercise dependent on the number of cabins, scope (man-minutes / cabin) and project duration (mandated by the owner) as it was impossible to compromise on the customer's lead time due to the owner's high opportunity cost. The calculated Takt time must accommodate both contractor's and owner demand perspectives and can be adjusted through reduction of buffer times or through further optimisation and acceleration to adjust customer demand (Haghsheno et al., 2016).

Table 2: Suggested process steps in selected approaches

Authors	Suggested Process Steps
Linnik et al. (2013)	1) Identify the trades that will work in the phase and how their tasks will be grouped together. 2) Gather information from trade partners. 3) Sequence trade groups and the trades within groups, identify bottleneck trades in each group, and roughly estimate their achievable production rates within the Takt areas. 4) Balance workflow determining Takt time in each sub phase. Adjust area structure if needed. 5) Use Takt time strategy to plan for resources, materials, and information.
Frandson et al. (2013)	1) Gather information. 2) Define areas of work (zones). 3) Understand the trade sequence. 4) Understand the individual trade durations. 5) Balance the workflow. 6) Establish the production plan.
Haghsheno et al. (2016)	1) Process analysis. 2) Agree working steps. 3) Establish standard room units. 4) Determine effort values. 5) Takt harmonisation. 6) Add buffers. 7) Takt control.
Heinonen and Seppänen (2016)	1) Defining Standard Workflow Within Construction Train – scope of work, set of tasks, workload value per task in minutes, Takt time is the time the system has available, select optimal crew size, assess logical and resource dependencies, bundle standard set of tasks (repeated each Takt time by same crew) into wagons, size buffer into Takt time, define material delivery and garbage collection points. 2) Define logistics – design one-piece flow of materials at first point of packaging, material delivery trollies, pick one cabin at a time. 3) Management roles and responsibilities – train drivers, (co-driver, logistics manager, logistics foremen)

While many of previous case studies were conducted on aspects of a single project, for example, internal drywall or on selected floors, Dlouhy et al. (2018a) reported Takt success on a large-scale project in Mexico. Extending beyond the pure construction phase, Dlouhy et al. (2017, 2018b) compared Takt in the construction and equipment phases of the same project and found recognisable benefits in collaborating and considering interfaces to upstream and downstream phases. Managing inputs and controlling variation is an essential component of Takt and was a specific focus of Chauhan et al. (2018) and Tetik et al. (2019) when examining prefabrication and logistics management in the context of Takt planning. On a similar theme, Vatne and Drevland (2016) found Takt implementation made it easy to spot errors and continuously steer the production proactively. However, despite much improved throughput time (reduced by 30%) and the project being lauded as successful, Alhava et al. (2019) found the flow of the Takt process allowed next tasks to proceed without full root cause assessment of errors, therefore allowing the errors to be repeated. This illustrates how using selected LC methodologies can highlight improvement opportunities in the existing process. However, to ensure delivery system advancement it is important that each opportunity is addressed by utilising the entire suite of LC methodologies - ultimately the project and stakeholders will develop their own Lean Project Delivery System. Table 3 summarises the key contributions of Takt to improving construction delivery.

Table 3: Takt contributions to improving project delivery.

LC Takt contributions to improving project delivery
Initiation & driving of continuous improvement culture.
Introduction of disciplined process analysis to trade workflow & supply chain inputs.
Focus on error-proofing and FMEA.
Importance of softer aspects alongside scientific approach.
Improved communication through visualisation of production goals.
Introduction of Lean concepts from TPS (value generation, customer focus, demand rate, throughput, production rate, bottlenecks, value stream mapping).
Visualisation of buffers.
Focus on balancing trade cycle times – from 15 minutes to a single day or 5 days (as determined mathematically).
Bringing stability to constructions supply chain inputs & logistics organisation to help control variation.

Stabilising inputs and effective logistics organisation are critical components of construction planning; Vatne and Drevland (2016) highlight this in a residential construction case study. Using Takt to plan materials and information inputs and well as coordinating Just in Time (JIT) deliveries is highlighted by Linnik et al. (2013, p.616), where Takt allowed supervisors and construction engineers more time to '…support the trades in determining quality requirements and in performing first run studies to test and refine the design of construction operations. They can spend more time on material and quality planning, and on root cause analysis of accidents, defects, and plan failures to avoid similar problems in the future.' An examination of flow in Takted projects (Binninger et al., 2019) found significant difference between planned and actual flow efficiency; the authors posit consideration of and balancing the mix of short delivery times of the product from the client perspective and stability and consistency of resources from the subcontractor's perspective. Flow and value-creation specifically from the client's perspective was examined by Lehtovaara et al. (2021), noting the proactive role of a client helps to put customer value in the centre of Takt production. Takt was also found to contribute positively to the flow of the trades while noting the importance of trust between stakeholders (Kujansuu et al., 2020). Practitioner awareness and knowledge of LC and Transformation, Flow, Value theory, as well as practice in all function of LPS, is an important enabler of Takt implementation;

logistics, supply chain, and multi-interface management requires technical and theoretical understanding of multiple LC and production system concepts.

The importance of the softer aspects also emerged in a comparison of collaboration and trade partner commitment in Californian and Finnish Takt implementations; Kujansuu et al. (2019) found the strong Lean culture established by the Californian companies allowed more reliance on social aspects and trust between stakeholders. People engagement, openness to new ways of working, and cultural aspects were highlighted as challenges by Schöttle and Nesensohn (2019). This highlights the importance of having the softer and people-related aspects of change-management in place when projects are introducing 'new' methodologies that challenge traditional approaches within construction delivery.

The strong knowledge on the technical aspects of production planning established a platform to build the Finnish model of Takt implementation. A study by Lehtovaara et al. (2020) recognised the construction sector was missing an opportunity to develop a shared understanding of systemic Takt production implementation. Academic discussion had primarily focused on how to technically implement Takt production in single projects while a few pioneering clients and contractors had experimented with aspects of Takt on elements of projects. However, a study of Takt application on a large-scale project ($1Billion) by Abou El Fish et al. (2022), allied to Dlouhy et al. (2018a) highlighted how Takt helped the construction team to properly control, organise, and place resources into projects to achieve desired goals. In an examination of Takt as an enabler for LC, Tommelein and Emdanat (2022) suggest Takt should be considered at early project strategic level, thereby assisting align design and supply chain. They add that a Takt implementation should be viewed as foundational to a framework that supports continuous improvement efforts. Additionally, Tommelein and Emdanat (2022, p. 876) conclude '…teams interested in implementing LPS on their projects start by designing their production system using Takt, and then design their LPS implementation to take advantage of all the opportunities production management and control offers.'

In conclusion, Takt research is beginning to impact project delivery with positive results witnessed as well as numerous challenges and improvement opportunities being identified. Takt started from consideration of directly applying production concepts from TPS, evolving from LBMS and LPS practices, considering technical and mathematical aspects, and testing hypothesis on different construction projects across geographical locations and cultures. Takt is now recognised as a viable and proven production system that can initiate systemic improvement in construction delivery.

RESEARCH QUESTION #3? WHAT ARE THE CHALLENGES/RISKS WHEN IMPLEMENTING LC TAKT PLANNING?

Vatne and Drevland (2016) identified a key challenge to Takt implementation on projects where the payment system (piece work) doesn't align with splitting of work packages into multiple Takt trains. This concern was also voiced in Lehtovaara et al. (2019) and Binninger et al. (2018) and was mitigated by a commitment to fully pay the subcontractors for a three-day trial even if no work was completed. According to Binninger et al. (2017), Takt has undergone criticism due to its scheduling rigidity during construction and its perceived hinderance to adjustments on a project. Handing over unfinished Takt areas tends to lead to more delays later because of irrational work sequences and correctional work (Dahlberg and Drevland, 2021), concluding that Takt is a fragile production system needing daily monitoring and readjustment. Extra management resources are possibly required as, according to Binninger et al. (2018), close supervision and comprehensive documentation are required to achieve and maintain low Takt times. Caution must also be exercised as Alhava et al. (2019) discovered the implementation of digital methods found a lot of waste in the project; despite reporting a successful project and achieving a 30% cycle time reduction a lot of waste was made visible.

The intensity of Takt planning can catch subcontractors and material suppliers unawares meaning procurement and payment models must align to suit (Lehtovaara et al., 2019). Additionally, incomplete design cannot become a cause of bottlenecks, drying times and critical tasks must be thoroughly planned, and Takt must become a holistic approach as opposed to just managing an individual construction phase (Lehtovaara et al., 2019). In a collaborative research paper (UC Berkeley and Aalto University) Lehtovaara et al. (2022) examined FMEA as a countermeasure to Takt failure and offer a framework for Takt control that uses the FMEA process logic. This study presented a systematic guideline for problem-solving in a Takt control context and illustrated examples of failures, failure modes, root causes, and control actions to assist in applying the framework.

CONCLUSION, RECOMMENDATIONS, & OPPORTUNITIES

It is evident from the IGLC literature that Takt has become a much-researched topic that has acquired attention from academics and practitioners alike. The examined studies are unanimous in agreement of advantages accruing from Takt implementation and a broad list of disruptive issues are presented. However, the authors assert such 'making-do' issues are an everyday aspect of construction delivery and it is only when such an intense but fragile framework like Takt challenges the status quo can practitioners truly acknowledge the amount of variation and variability that exists.

Takt is now recognised as viable and proven production system that can initiate systemic improvement in construction delivery. To ensure continued advancement it is important that each identified improvement opportunity is addressed by utilising the entire suite of LC methodologies and ultimately the project and stakeholders will develop their own Lean Project Delivery System and culture. Allied to the development of this improvement culture is the importance of having the softer and people-related aspects of change-management in place as efforts that challenge traditional construction delivery approaches can meet active or passive resistance.

Despite the pioneering research and advancement, studies have highlighted the need for a consistent globally agreed framework that aligns thought leader's ideal-state perception of Takt implementation. This would accommodate geographical distinctions, cultural and softer aspects, and encourage a more holistic implementation both upstream and downstream of the specific construction execution phase. Researchers must also be cognisant that innovation must be encouraged as consistently testing hypotheses and methodologies on live projects exposes the daily challenges that stifle productivity improvement within the sector.

Every project should consider Takt from the outset in its high-level strategic planning and continue to assess where several sub-Takt plans can contribute to the execution of the project, assisted by LPS and the broader suite of LC techniques.

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IMPLEMENTING LEAN METHODS FOR FACILITY MAINTENANCE MANAGEMENT

Kiran Rambhau Janjalkar[1], Abhishek Raj Singh[2], and Venkata Santosh Kumar Delhi[3]

ABSTRACT

The breakdown of facilities in a built environment results in inconvenience to the stakeholders due to the downtime (DT) experience. The facility DT can be brought down through proper facility maintenance management (FMM). Within FMM, different processes occur to make the facility work normally. These activities of FMM are sometimes planned and often executed when a facility undergoes breakdown. This study targets to understand the implementation ability of lean methods in situations when a service of a built environment has failed and the FMM system tries to bring it back to normal functioning. An educational institute's FMM process to address DT is mapped using value stream mapping (VSM), and delays associated with the current process are captured. This mapping helped in identifying delay causes like material unavailability and administrative delay. The research utilizes the 5S (Seiri, Seiton, Seiso, Seiketsu, Shitsuke) and Just In Time (JIT) methods of lean to improve the FMM process, and implementation of these methods resulted in achieving resolution time closer to the time expected by the stakeholders utilizing the facility.

KEYWORDS

Facility maintenance management, lean philosophy, 5S, JIT, VSM

INTRODUCTION

The concept of facility management (FM) is defined as an integration of people, process, technology, and place that can ensure the functionality of the built environment (Atkin & Brooks, 2015). Within FM, the facility maintenance management (FMM) shares the most (65% ~ 85%) of the FM cost (Chen et al., 2019). Any built-up facility requires maintenance to perform satisfactorily and makes the buildings habitable and serviceable for the stakeholders. Unlike residential buildings, the built-up facilities of an educational institute are designed to serve different functions to a large population of stakeholders. With an increase in globalization, the facilities available at an educational institution become a criterion for the stakeholders to make decisions (Cubillo et al., 2006; Price et al., 2003). The Institute facilities are essential in attracting researchers by providing a suitable environment for faster knowledge creation (Fleming & Storr, 1999). Good infrastructure for educational institutes creates the chance to attract and sustain global talent.

Maintaining such facilities has a significant cost that could vary from 15% to 70% of the initial investment cost depending upon the type and size of the project (Fraser, 2014). Generally, these maintenance costs are proportional to the downtime (DT) of the system or an asset

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(Mostafa et al., 2015). The DT can be defined as the time interval when the system/equipment is down for maintenance activity until it is back to its normal working condition (Tinga, 2013). The DT is impacted due to the presence of non-value-adding activities (NVA) and wastes in the process of maintenance (Sawhney et al., 2009). Due to increased DT, there is a chance of overloading the existing working facilities, which may further lead to the failure of the existing system. Frequent occurrences of increased DT in facilities management may have a severe impact on the reputation of any organization (Atkin & Brooks, 2015). Hence, efficient FMM is imperative for the smooth functioning of the day-to-day operations of an organization.

The lean philosophy provides waste minimization methods while creating value for the stakeholders (Denzer et al., 2015). Lean philosophy mentions the elimination of waste (Viana et al., 2012) and reducing NVA to improve the process (Mostafa et al., 2015). Previous research studies have focused on lean implementation for construction and supply chain management, but a narrow focus is given to FM (Gao et al., 2020; O'Reilly et al., 2019). With a rising focus on FM as a strategic element for revenue generation, the FMM is recognized as an essential process (Mostafa et al., 2015). The present study attempts to highlight the NVA in the process of addressing the complaints of the stakeholders in an educational institute. The focus remained on investigating the applicability of lean tools for FM, and some lean methods like 5S, Just-in-Time (JIT), and Value Stream Map (VSM) are utilized to bring down the DT. The study considers unplanned DT for facilities and presents a lean approach to handling and improving the process of FMM in an educational institute.

REVIEW OF LEAN-FM SYNERGY

The FMM comprises but is not limited to activities that are scheduled and planned. In the event of a system breakdown, the stakeholders suffer due to unplanned DT. An unplanned DT request for maintenance indicates a 'pull' of value from the system. Similarly, lean works on the principle of creating value for the stakeholders, i.e., the services upstream should be produced when the stakeholders downstream require them (Gao et al., 2020). In an educational setup, the service DT impacts the habitants, and a quick-fix approach is traditionally adopted. It is essential for these services to be functional to deliver value to the stakeholders. The breakdown of any service in an educational institute is an unanticipated event that makes it challenging in comparison to other sectors like construction, and supply chain management, where lean implementation is proven beneficial. This study attempts to utilize some lean tools like 5S, JIT, and VSM to deliver value to the stakeholders just-in-time.

5S AND JIT FOR FM

The philosophy of 5S originated in Japan (Chandrayan et al., 2019). It is an acronym for five different Japanese terms 'seiri (organization of the workplace, sorting, elimination of unwanted inventory), seiton (neatness, set in order, place for everything), seiso (cleaning, shine), seiketsu (standardization, constant place for things, constant rules for organization of things), and shitsuke (sustain, discipline)' (Kobayashi et al., 2008). The Western literature from the UK and USA mentions 5S as a technique or a tool to improve working conditions. The lean studies report the implementation of 5S as an easy and uncomplicated process (Bayo-Moriones et al., 2010). Alongside process improvements, the 5S implementation is also reported to channel other lean tools like JIT (Kobayashi et al., 2008). The JIT concept was framed by Taiichi Ohno in Japan (Kumar & Panneerselvam, 2007). The JIT emphasizes continuous waste reduction and eventually eliminating all forms of waste (Brown & Mitchell, 2017). The JIT concept of lean focuses on providing the required items at the right place and right time. Research studies indicate the JIT implementation in synergies with pull planning systems to generate value (Mumani et al., 2022). In attempts to understand the bottlenecks of push-pull systems, another tool highlighted in lean literature is VSM.

VSM FOR FM

VSM is an essential tool associated with lean methodology and is extensively used to map information and process flow (Sawhney et al., 2009). VSM is an effective tool for identifying and resolving the issue that can be seen in current approaches. This allows for the maximization of performance at the project level (Pothen & Ramalingam, 2018). It helps to map the process and identify the wastes and their sources in the process. Application of VSM is a five-stage process that starts with selecting an activity, developing a current state map, analyzing waste and developing a future state map, proposing an action plan, and its validation. The lean research presents the applicability of VSM to map processes using one key metric of value-adding time. These maps primarily capture the process flow through icons and symbols, following which the value-adding activities, non-value-adding activities & non-value adding but necessary activities time are measured (Mostafa et al., 2015). Although the planned FMM activities might appear as non-value adding to the stakeholders when an unplanned DT strikes, the FMM becomes a value-adding activity.

RESEARCH DESIGN

The DT of services at an educational institute impacts the habitant's academic achievements and brings a bad reputation to the institution (Lok & Baldry, 2015). Therefore, to mitigate the ill effects of service breakdown, an efficient FMM system is needed. This study reviews the existing FMM system at an educational institute and presents opportunities to improve using lean methods. Figure 1 presents the sequential procedure followed in this study to understand the implications of implementing lean methods to FMM. The initial stage of this research starts with collecting data related to the DT encountered by the stakeholders of the built-up facilities in the institute considered for this study.

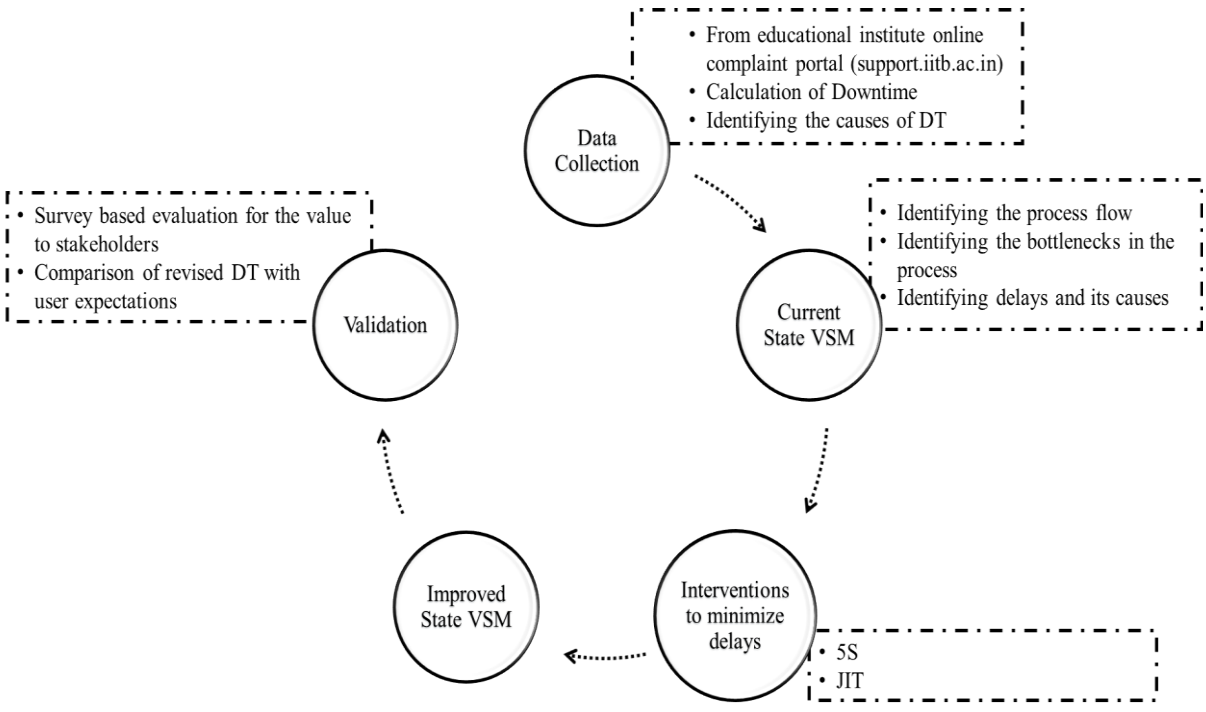


Figure 1: Methodology followed in this Study

Upon data collection, the current state VSM for the existing FMM process is mapped, targeting two different delays, and bottlenecks in the FMM process are identified. Although the current state VSM is followed with future state VSM in lean research, the researchers for this research targeted to implement 5S and JIT methods of lean to address the bottlenecks identified from current state VSM. After the implementation of lean methods, an improved state VSM is developed to understand the improvement achieved. Finally, to verify the observed improvement in the improved state VSM, the resolution time expectations of the stakeholders residing in the institute are compared with the achieved time to resolve complaints.

DATA COLLECTION AND CURRENT STATE MAP

In an attempt to understand the delays in FMM, a web-based DT complaint registering portal is utilized to collect the complaints of the stakeholders. The support portal can be accessed through a web address mentioned in Figure 1. This portal allows the stakeholders to report any maintenance requirements from the 17 student accommodation buildings of the institute. After a complaint is raised, it is transferred to a concerned administrative section, following which a required action is initiated against the complaint. For our context, the Down Time (DT) is the duration between registering a complaint and closing the same. As per internal guidelines, registration can only be done by the users through the portal and closed by the concerned staff after verbal confirmation by the users.

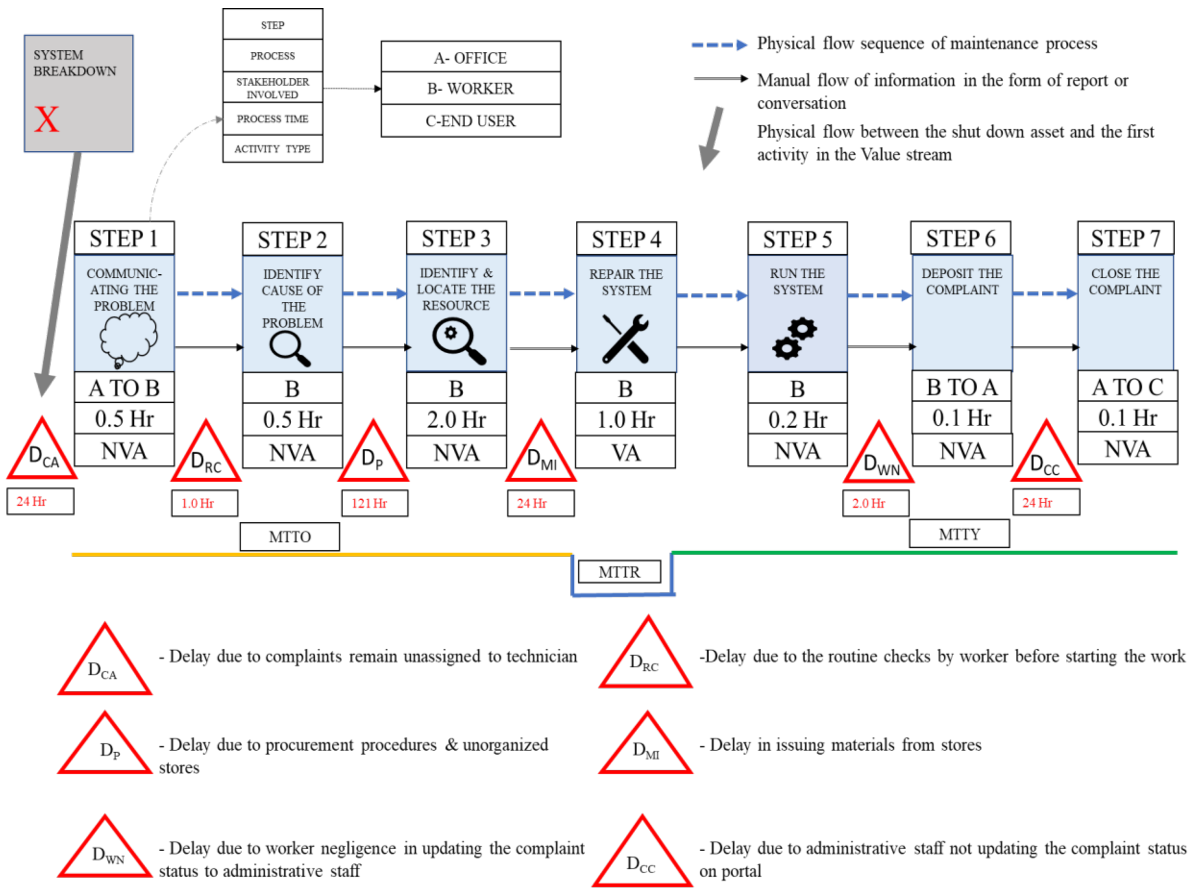
The VSM of the current process is prepared to map the activities, and the associated time with each activity is mapped accordingly to get an understanding of Mean Maintenance Lead Time (MMLT) (Sawhney et al., 2009).

CURRENT STATE VSM

The first step in plotting the current state is determining the steps and processes involved in the existing FMM system of the educational institute. The maintenance process is triggered by detecting and reporting the failure of an asset or system (Marttonen-Arola & Baglee, 2020). Such type of maintenance comes under corrective and unplanned maintenance strategies.

Once a maintenance work request is raised on the support portal of the institute, the concerned administrative person collects the requests and forwards it to the concerned technician of the department only after a bulk of requests are accumulated. Then, the technician performs a manual inspection of the reported problem by making a visit to the respective building from which the end-user has placed the complaint.

Then a request for necessary resource requirements to rectify the defect is raised by the technician. The requested resources will be made available to the technician either from the inventory if the material is available with the institute material store or is procured from retail vendors. Then, the technician will fix the complaint, take confirmation from the user, and deposit the complaint to the office for closure. The office staff will then mark the complaint status as resolved on the complaint management system. Figure 2 presents the current state of the maintenance process, where seven main activities are identified in the process communicating the problem, identifying the problem, identifying, and locating the required resources, repairing the system, running the system, depositing the complaint, and closing the complaint. The process time (PT) associated with each activity in the developed current state VSM is taken from the visual observations and experts' opinions.

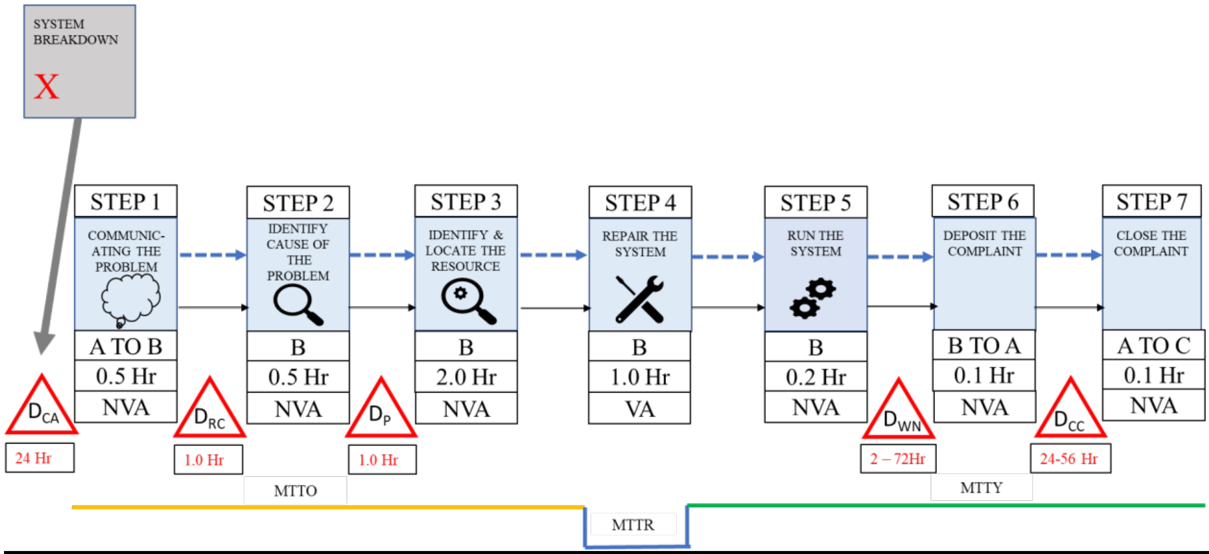


200.4 hrs.	Mean Maintenance Lead Time	MMLT
173.0 hrs.	Mean time to organize	MTTO
1.0 hr.	Mean time to repair	MTTR
26.4 hrs.	Mean time to yield	MMTY
1.0 hr.	Value adding time	VAT

Figure 2: Current State Map for Complaints Delayed Due to Material Unavailability

In the entire process of rectifying the defect, only repairing the system activity is value-adding to the end-user, whereas the rest of the activities remain non-value adding. From the above Figure 2, the Mean Maintenance Lead Time is 200.4 hours, i.e., approximately eight days, and there is a significant delay of 121 hours in locating the resource termed as delay D_P in Figure 2, resulting in a long DT of the services. It is identified that a significant time portion is spent on organizing resources to address the end-user problem. This is due to the time lost in searching for materials in the inventories, and sometimes the material is not available with the store department resulting in procuring the resources from the market; such delay in material search and procuring results in longer DT of the system.

Therefore, to understand the delays in the system where the actual DT of services is lesser than the recorded DT, another VSM is prepared, as shown in Figure 3.



MMLT	MMTO	MMTR	MTTY	VAT
56.4-158.4 hrs.	29.0 hrs.	1.0 hr.	26.4-128.4 hrs.	1.0 hr.

Figure 3: Current state map for complaints delayed due to administrative delay

From Figure 3, the maximum MMLT is 158.4 hours, i.e., approximately six days. The end user is not concerned about delays D_{WN} and D_{CC} because the complaint is resolved in 30.0 hours, and the services are working again. However, such complaints cause overloading of the complaint management system, which overall affects the efficiency of the facilities management system. The delay in updating the status of the complaints on the portal does not provide the current availability of the resources for attending to any other system breakdown, thus resulting in a delay in attending to the complaints that keep on piling up due to administrative negligence. Timely updating of the complaint status will bring down the MTTY and help in identifying resource availability. Consequently, by bringing down the MTTY, the other DT associated with other system breakdowns can be brought down by the timely resolution of the complaints. Hence, it is essential to reduce waste associated with material procurement and delays in updating complaint status.

RESULTS

The data for this study is collected on the complaints raised between August and September 2022. A total of 349 complaints were received, among which the carpentry and plumbing works are found to be the major complaints. Other complaints include masonry, fabrication, and cleaning-related works. A breakdown of complaints is presented in Table 1.

Table 1: Complaint data of 17 buildings

Month	Plumbing	Carpentry	Other	Total
August 2022	88	106	20	214
September 2022	62	61	12	135

Upon receiving the data of complaints registered in the period mentioned in Table 1, the complaints are studied with the help of the concerned technicians to extract the possible reasons for the delays. From the obtained complaints data, ten causes of delays are identified, as shown in Figure 4, namely workmen (technician) unavailability, material unavailability, duplicate complaints, multiple departments involved, major modification work required, works require outsourcing, unique material requirements, delays due to external sources, end-user unavailability, and administrative delay.

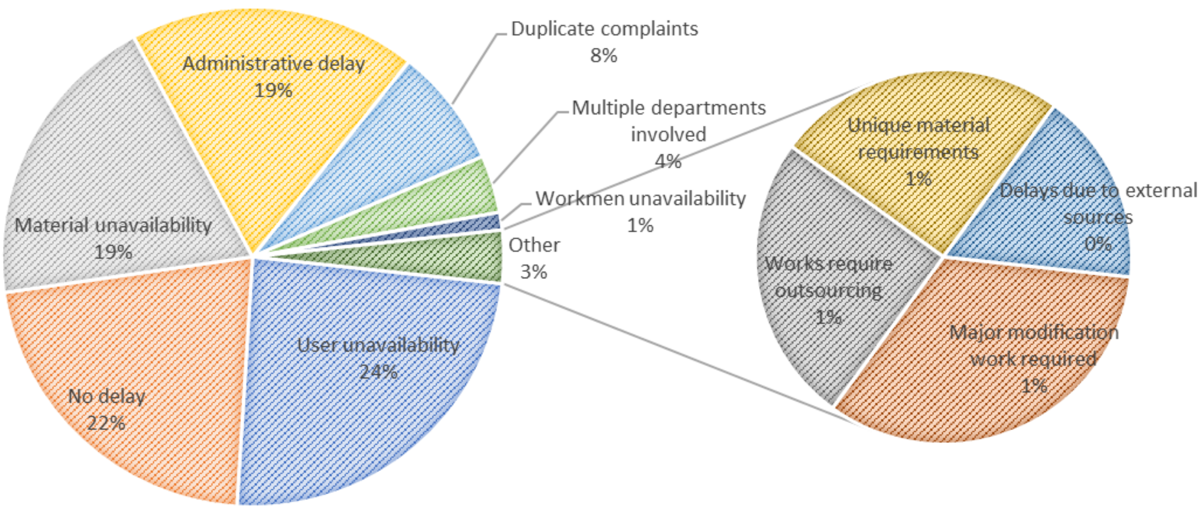


Figure 4: Distribution pattern for no delay and reasons for delay

It is observed that a significant share (24%) of the DT is due to the unavailability of the user when the maintenance team comes to address the problem raised by the stakeholder. This share of facility DT is hard to address as the end user for whom the value generation is targeted by addressing the raised concern is unavailable. Thus, such complaints and the DT are not addressed in this study. Following user unavailability, 22% of the raised complaints are addressed as quickly as possible, and the services are restored with no delay. Since the FMM comprises but is not limited to the involvement of administrative, technical, and end-user stakeholders, the other 38% share in the delay of addressing complaints is shared equally by the administrative and the material unavailability to address the problem. 19% of complaints indicated DT associated with material unavailability. It is primarily due to the initial time lost in searching for the appropriate material for replacement or sometimes due to the unavailability of the material in the inventory. It is observed that the unavailability of the material is identified upon a significant amount of time lost in searching the inventory maintained by the maintenance department, consequently increasing the DT.

Another share of complaints (19%) results in delay because of system inefficiency in closing the complaints and marking them resolved. It means that the raised complaints are attended timely, but they are not closed immediately upon successful resolution on the portal by the administrative staff and thus are categorized under administrative delay. This category of the complaint will be considered under as waste category, as the delayed closing of the complaint will not have any impact on the DT of the facilities.

Two categories of complaints - material availability and administrative delay, are selected for the application of appropriate lean methods.

INTERVENTIONS TO MINIMISE DELAYS

From the current state of VSM, it is clear that there are wastes involved in the process flows. The MTTO is approximately 173 hrs. which equates to more than a week's time to organize the resources to carry out the actual repair. There are multiple delays associated with the delayed resolution of complaints due to material unavailability, as shown in Figure 2. Among these delays, the D_{CA} of almost a day indicates the delayed assignment of the task to the technician. A provision of immediate allotment after receiving a complaint is introduced to address this delay. After allotment of the task to the technicians, delay D_{RC} is observed where the technicians have to manually inspect the nature of the registered complaint, and such visits result in loss of time due to travel to the location of service under DT. In an attempt to minimize the travel time only for inspection, an option of uploading the photographs of the service requiring maintenance is asked from the user in an online complaint portal of the educational institute.

This approach of collecting information related to the service requiring maintenance is developed so that upon receiving the complaint along with photographs, the material procurement step of the process can be initiated as soon as possible. Within MTTO, a significant delay is noticed between the process of 'Identifying the cause of the problem' and 'Identifying and locating the resource.' Although the process of identifying and locating resources takes two hrs., the initial search process for the resources consumes the delay time and results in longer DT. The authors observed that the delay in resource search also results in vain if the appropriate material is not found in the institute's inventory.

Upon noticing the material unavailability, the material procurement step from external sources starts. Therefore, the search time spent locating an unavailable material in the inventory results in unnecessary longer DT of the system. Thus, to minimize the search time for unavailable material, the inventory unit is redesigned by implementing the 5S concept of workplace design, as shown in Figure 5. As the cluttered place of storing materials became organized, the situation of the available inventory became more precise, and such organization is also implemented in record keeping of the inventory.

Figure 5: 5S Implementation in the Inventory Room

Upon identifying material unavailability, the procurement of materials is initiated, for which a separate contract is created that results in a time delay. Some lean literature presented that this type of waste can be eliminated by adopting the Just in Time (JIT) lean concept. The JIT highlights no requirement for inventory, and the material is directly procured from the suppliers. Therefore, to implement JIT, an annual maintenance and supply contract is proposed for materials used in the buildings for which complaints are received. So, the vendor can be asked to carry out the maintenance work when required. In this way, the delay due to material procurement is reduced to an extent, and DT is shortened.

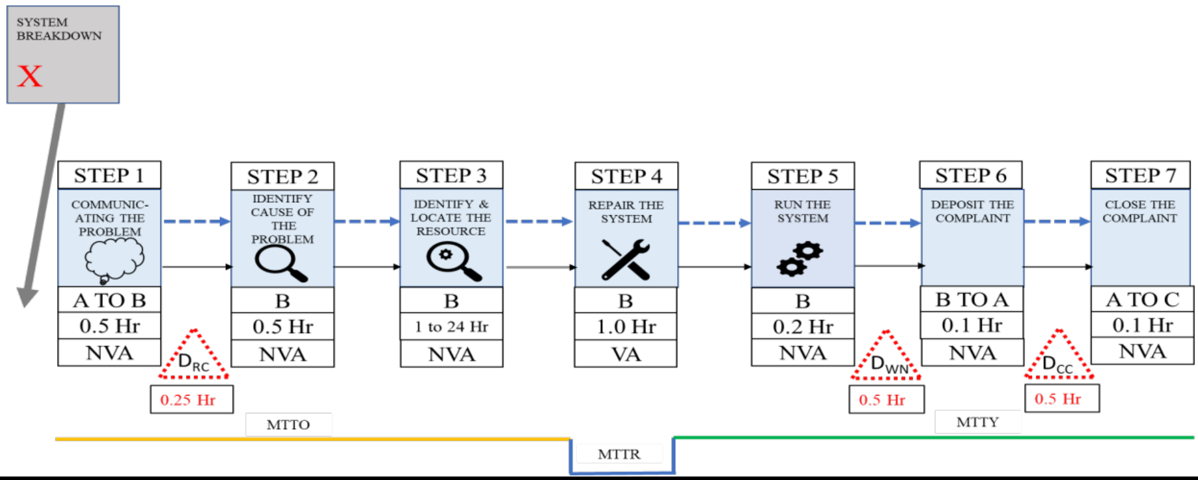
Thus, how the wastes related to the process before the repair work starts and the material unavailability are attempted to be minimized by applying lean philosophy.

Other delays D_{WN} and D_{CC} is related to the closure of the registered complaint that results in MTTY. These delays do not create value for the end user, but it overloads the complaint management system and impacts the efficiency of the FMM system. This waste can be easily eliminated by transferring the information as soon as the complaint is attended to and the services return to normal functioning. It is proposed that the status of the complaint upon successful resolution should be reported JIT to the administrative staff for closing up the complaint and releasing the resources from the task. This JIT reporting will not only bring down the recorded DT on the portal but will also affect the other services under DT, as the resources are now available to address those complaints.

DISCUSSION

The implementation of web-based direct allotment of complaints and allowing users to report issues with photographs of the service under DT are implementations of computer-based (Smith & Hawkins, 2004). This approach of reporting the issue improved the information flow between the stakeholders and indicates the essentiality of information flow for improved flow in the process (Dave et al., 2014). Also, lean concepts like 5S and JIT are now incorporated into the current FMM process flow, and the process mapping is done to assess the impact. 5S is implemented in the institute's stores, where the material is kept and collected by technicians for attending to the complaints.

JIT is implemented where an annual maintenance contract (AMC) is prepared for the supply of various materials and services as and when required. This will reduce the material waiting time in the process. These lean methods for process improvement are incorporated into the existing process to bring down the MTTO. Figure 6 shows the proposed improved VSM.



MMLT	MMTO	MMTR	MTTY	VAT
4.65-27.65 hrs.	2.25-25.25 hrs.	1.0 hr.	1.4 hrs.	1.0 hr.

Figure 6: Improved State VSM for FMM in an Educational Institute

It is evident from the VSM that the delays contributing to MTTO are now reduced. It might be argued that the PT of identifying and locating resources has increased, and this increased time is not commonly observed but only extends when the AMC contractor does not have the required material. Although the end-user is not delivered any value in this time period, the delay in the FMM system is now transferred to the AMC provider process flow. Outsourcing non-core activity is suggested as a lean practice that enables collaborations (Cudney et al., 2020), and improved services can be availed (Lok & Baldry, 2015). Another delay time in MTTY is handled by making the information flow follow the JIT concept of lean philosophy.

USERS' EXPECTATIONS ON DT VS ACHIEVED RESOLUTION TIME

The study results are limited to an educational institute where students worldwide come and study. These students reside in 17 student accommodation buildings located within the institute's premises, and thus the service DT for the facilities is considered for improvement;

those are reported as complaints on the institute portal. To understand the improvements obtained from implementing lean in the FMM process of the institute, a survey is drafted for the authorities in these 17 buildings. The drafted survey asked questions related to the expectations of the end-users in terms of the expected time to procure materials to address the DT and the expected resolution time for a complaint raised on the portal. The authorities in charge of maintaining the facilities at each student accommodation building participated in the survey. A total of 23 responses are collected, and it is indicated by the authorities, as presented in Table 2, that they expect a time duration varying from 1 hour to 3 days to be spent in the procurement of materials in instances when the material is not available in the institute's inventory.

Table 2: Distribution of Expected Time Indicated by Stakeholders

Duration	1.0 to 3.0 hrs.	4.0 to 10.0 hrs.	11.0 to 20.0 hrs.	21hrs. to 1.5 days	1.5 to 3.0 days
Material procurement	13%	22%	17%	26%	22%
Resolution of complaint ticket	65%	17%	0%	9%	9%

The respondents also indicated that the resolution time for a complaint registered with the FMM of the institute should not exceed 3 hours when the required material is available, as shown in Table 2. This duration remains less than the achieved MMLT after incorporating lean methods into the FMM process.

Although the achieved MMLT remains higher than the stakeholders' expectations, the lean method implementation has achieved a resolution time closer to a minimum of 5 hours. This resolution time indicates lesser DT; thus, lean implementation in the FMM process of an education institute has created value for the stakeholders.

CONCLUSION

The study presented a lean approach to improving the FMM process of an educational institute. Lean methods like 5S, JIT, and VSM are employed in this research, where VSM proved helpful in mapping the FMM process and highlighting delays in the existing process. The 5S and JIT implementation indicated improvements by reducing the DT observed due to delays in the process of the FMM. The primary delays identified in this study are related to material unavailability and administrative delays. The reduced delays indicate the process followed in the educational institute considered in this research. However, the results are not typical but indicate process improvement through implementing lean methods in the FMM. The study presents an implementation of lean in a reactive scenario when a service experiences DT whereas the essence of FMM is to prevent DT; therefore, the study will be continued to identify the advantages of lean in a proactive FMM scenario.

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A VDC FRAMEWORK PROPOSAL FOR TIME OPTIMIZATION IN DIAMOND DRILLING OPERATIONS FOR MINING

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ABSTRACT

A Virtual Design and Construction (VDC) framework proposal is presented for time optimization in diamond drilling operations for a mining exploration project. The mining project is located in the Huancavelica region of Peru and is currently in the underground exploration phase through diamond drilling drillholes. The geology team uses diamond drilling samples to estimate the total mineral reserves of the mine, and they have projected 13,278 meters to be drilled. The VDC framework proposal's application allowed a better understanding of diamond drilling processes to support the variability source reduction related to equipment, maintenance and operational tasks. The results showed a time optimization in the diamond drilling operation of 10%.

KEYWORDS

VDC, diamond drilling, mining explorations, project management, process optimization.

INTRODUCTION

Mining exploration projects focus on generating new prospects and exploring them to locate and define the ore bodies that lie in them (Marjoribanks, 2010). The present investigation was conducted in a mining project's exploratory phase located in the department of the Huancavelica region of Peru by diamond drilling. This exploratory project aims to estimate ore reserves by exploring identified veins. The diamond drilling exploration consists of drilling holes previously identified and approved by the geology department with a specified depth angle and azimuth. For this project, the drilling depths were an average of 300m long. The geologists first analyze the cylindrical-shaped rock samples collected from the drilling process and then send them to a laboratory for further investigation. According to Uvarova et al. (2015), this exploration campaign is summarized in drilling, collecting, logging, and cutting diamond cores for laboratories that will analyze them.

For the exploratory activities of the project, a company specialized in diamond drilling was commissioned. They had two drilling machines of similar size and capacity during most of the project and worked in conjunction with the exploration department of the mining company. This department was responsible for indicating the points to be drilled and preparing the samples for subsequent shipment to the chosen laboratory.

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The drilling company's operations started in April 2022, and several drilling samples were obtained during the first 5 months of work. However, the recovered cores' quality was below the exploration department's standards. It was observed that the drilling speed was higher than usual, resulting in defective samples. This situation obligated the company to issue an order to the drilling company to slow down the speed, reducing the number of cores but increasing the core quality. This order changed the expected production from 20% to only 0.05% over the monthly target, as shown in Figure 1.

The objective of the exploration campaign of the mining company was to use the cores obtained between the start of the exploration on April 18, 2022, until October 31, 2022, for reserves estimation. There was no established metric for the number of cores to be obtained at the end of the established period. However, considering the minimum goals agreed upon with the drilling company, 1,100 meters per machine per month, this period should be completed with at least 13,278.06 meters of diamond cores. Due to the drilling speed reduction, the target value of 1,100 meters per month was barely reached, resulting in 1,453.01 meters being executed in the remaining two months.

The literature review revealed several studies on productivity optimization in exploratory mining projects and diamond drilling operations, but these studies differed considerably. For instance, Boeksr (1930) proposed a new design of a diamond drilling machine capable of reaching greater depths and speeds. In contrast, Gao (2021) focused on optimizing time through a new method of performing depth measurements of diamond drill holes. Another study by Mustafa et al. (2021) investigated optimizing productivity by controlling drilling parameters to increase drilling speeds.

To not affect the estimation of mineral reserves, which depend on the exploratory campaigns, a VDC framework was developed focused on increasing productivity and complying with the standards of the exploration department.

Virtual Design and Construction (VDC) is a methodology created by the Center for Integrated Facility Engineering (CIFE) at Stanford University in 2001. According to Del Savio et al. (2022) and Rischmoller et al. (2018), VDC refers to utilizing multidisciplinary performance models in design and construction projects. VDC is composed of: Client Objectives, Project Objectives, Production Objectives (Production Metrics), Controllable Factors, Integrated Concurrent Engineering (ICE), Building Information Modeling (BIM), and Project Production Management (PPM) (Del Savio et al., 2022). The VDC components are summarized in a framework called VDC Framework, which integrates them and enables better management for developing a project. By fulfilling their controllable factors and production objectives, the PPM, ICE, and BIM components seek the success of the project's objectives, which, consequently, also achieve the client's objectives since they are directly linked to each other. According to Rischmoller et al. (2018), process (PPM), organizational (ICE), and information (BIM) knowledge must be integrated to produce the highly integrated systems necessary for a high-performance project.

The literature review shows limited examples of the VDC methodology implementation in mining projects, mainly because its application has been initially focused on the construction industry. Del Savio et al. (2022), who complied 7 case studies of the VDC application, showed that this methodology achieves optimization of costs, time, resources, and quality of the projects, which is why it was decided to apply and demonstrate its potential use and advantages in the mining industry.

This research seeks to demonstrate the efficacy of the VDC methodology as a viable alternative for overseeing mining exploration initiatives that involve diamond drilling. By implementing the VDC methodology, this study aims to highlight how it can optimize the exploration process, improve the quality of collected data, and ultimately lead to better decision-making in the mining industry.

METHODOLOGY

The methodology used for the research development includes collecting data from one of the project's drilling rigs during the first 5 months of operations from a 7-month project. It was collected from the daily reports sent by the contractor and entered into a database made for the exploration progress on an Excel file. The data collected corresponds to the physical progress, the detailed use of working hours for each shift, and the work processes used. With the information collected, it was identified the main sources of variability that generated a lower number of drilling hours. The methodology consisted of developing the VDC framework, defining its components, establishing the new processes with PPM, and identifying the variability sources. The corresponding results were obtained for each component of the VDC Framework.

DATA OBTAINED

The project worked with two drilling rigs during most of the project. Drilling rigs DE-130 and H-200 models were used, being the H-200 model replaced by a DE-140 model on August 21, 2022. The DE-130 drilling rig, which worked from the beginning of the project on April 18, was withdrawn on October 12, 2022, leaving only the DE-140 drilling rig until the end. Due to these circumstances, the data collected that served for the VDC implementation was from the DE-130 drilling rig, which has complete data for the 5 months before the order to decrease the drilling speed, and it is with the work of the DE-140 drilling rig that the VDC methodology was implemented. The drilling rig changes caused a week's loss in which the project lost at least 300m of samples considering the average daily drilling.

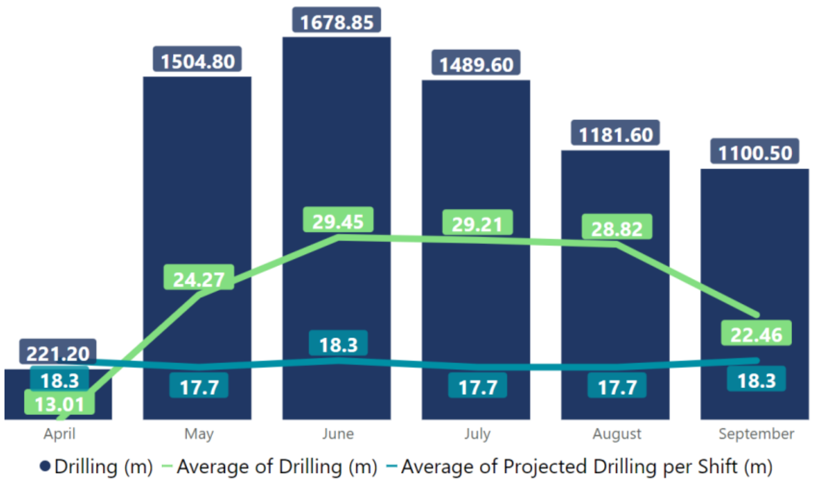

Figure 1: Monthly and daily drilling performance for the DE-130 drilling rig

As shown in Figure 1, the DE-130 rig performed well, surpassing its monthly drilling target of 1,100 meters by 24.59% (except for April 2022, when it started operations). It maintained an average throughput of 26.65 meters/shift during high-speed drilling months but decreased to 22.46 meters/shift (down 16%) in September 2022, slightly exceeding the monthly target by 0.05%.

Two main variability sources were identified, working in collaboration with the DE-140 team (Figure 2): those attributed to the drilling and mining companies. These variability sources were identified through the processing of data and the creation of statistical graphs, as shown in Figure 3. The lost hours were classified by type and then shown on graphs, allowing their better understanding and effect on the project.

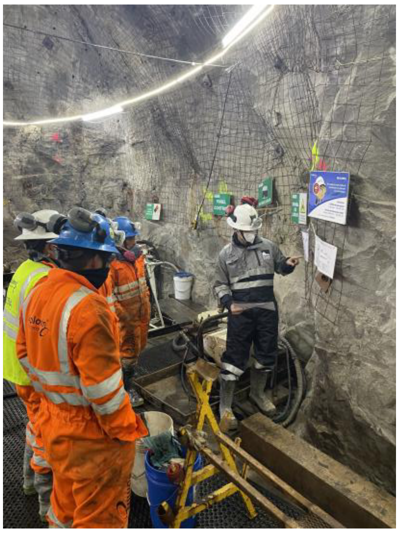

Figure 2: Introducing the DE-140 team to VDC.

Among the sources of variability attributable to the drilling company shown in Figure 3, corrective maintenance (maintenance caused by malfunctions of the drilling rig) and operational delays (delays caused by the drilling team's operations) stand out, accounting for 10.31% and 10.00% of the drilling hours executed.

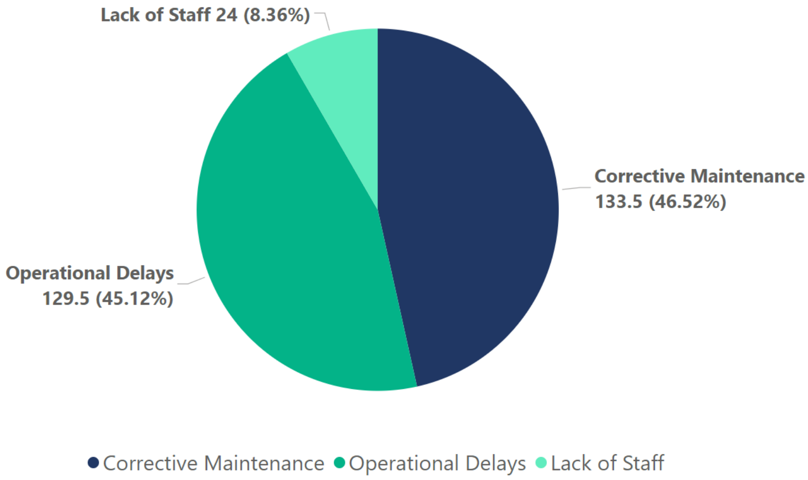

Figure 3: Variability sources attributable to the drilling company

The sources of variability attributable to the mining company correspond to the standby times that are the company's responsibility. The three sources of variability identified and shown in Figure 4, corresponding to standby, total 82.5h and are equivalent to 6.38% of the drilling hours.

The process flow shown in Figure 5 was obtained by observing the joint work of the mining and drilling companies and by interviews with the key stakeholders, such as the operations chief and mine superintendent. A considerably basic process flow is evident in which there is no differentiation by area involved or integration between them. The process consisted of the morning and night meetings before the beginning of each shift, finishing with the sending of the daily report before the next day's morning meeting.

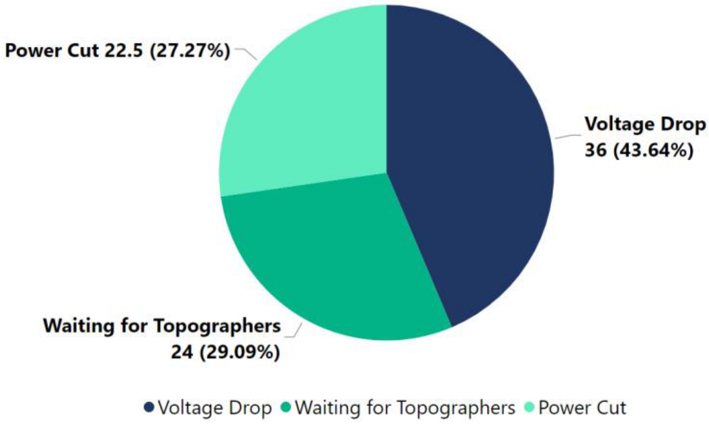

Figure 4: Sources of variability attributable to the mining company

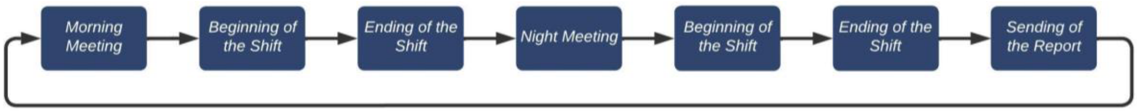

Figure 5: Work process before VDC

PROPOSAL APPROACH

The work proposal for implementing VDC in the project should focus on meeting the client's objective of 13,278.06 meters of drilled cores to estimate reserves. Next, the project's objective was defined. Focused on implementing time optimization by mitigating sources of variability to increase production to 14,606.87 meters of core drilled, which is 10% more than the client's objective. Once the implementation objectives were defined, the PPM, ICE, and BIM components were designed.

The PPM component, focused on the processes and operation, has as a production objective the reduction of variability sources to less than 10% of drilling hours and, as a controllable factor, the review of improvement proposals obtained in the ICE sessions. The ICE component, focused on the organization, has as a production objective the resolution of 100% of the improvement proposals by the stakeholders received during its sessions and the number of ICE sessions performed per day as a controllable factor. Finally, the BIM component, focused on information integration, was implemented through control dashboards that were connected to an Excel database, where PPM production objectives are displayed in an interactive and easy-to-understand manner so that all team members could see updated project information and make decisions not only in the ICE sessions but also in the field. It had as a production objective the time to receive drilling reports, which should be <=15 minutes from the departure of the drilling rig from the mine, and as a controllable factor, the number of dashboard updates per day. The BIM production objective is due to the time it takes to send the daily reports since they were only used to record the progress and calculate the valuations. Both reports were sent together once a day, which caused a delay in the reception and processing of the information.

RESULTS AND DISCUSSIONS

IMPLEMENTATION OF PROPOSAL

The VDC implementation approach is translated into the VDC Framework, which groups the VDC components in a graphical and interrelated way to fulfill their integration. In addition, it includes explicit specifications of customer and project objectives, performance measurement, and project models (Kunz & Fischer, 2020), as seen in Figure 6.

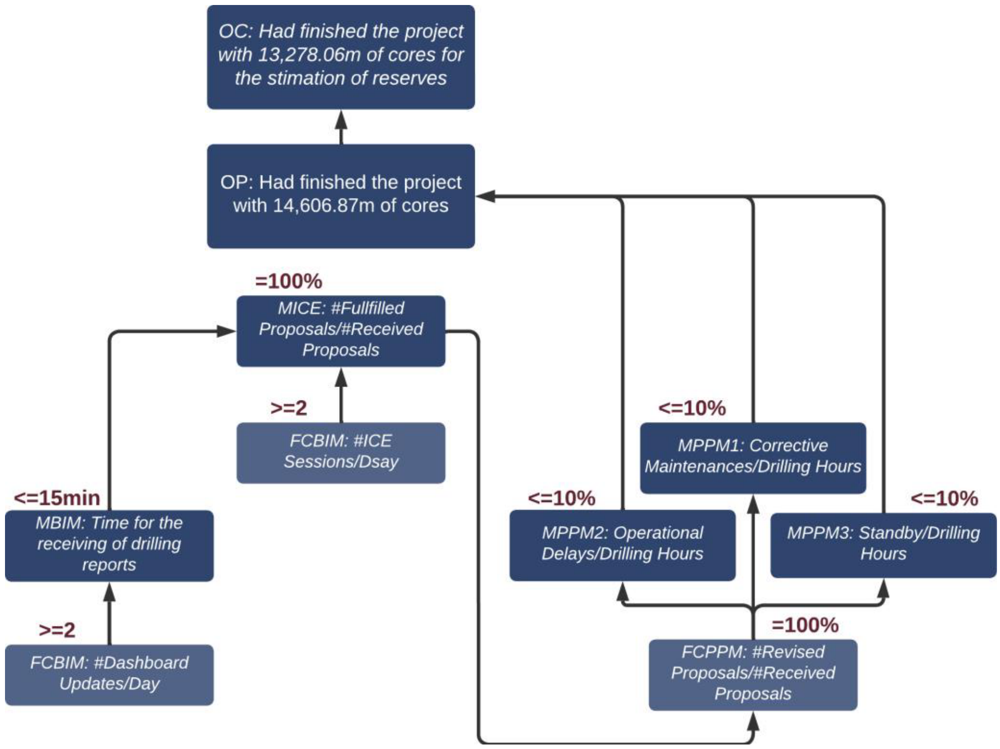

Figure 6: VDC Framework

The VDC Framework allows optimal visualization of the methodology and its implementation. Likewise, the process flow between the different areas shown in Figure 5 had to be updated according to the new needs demanded by the proposed VDC implementation, as shown in Figure 7.

According to the VDC Framework, the updated process flow integrates the different areas, focusing on productivity by sharing information and reducing query response latency, enabling decision-making before and during operations.

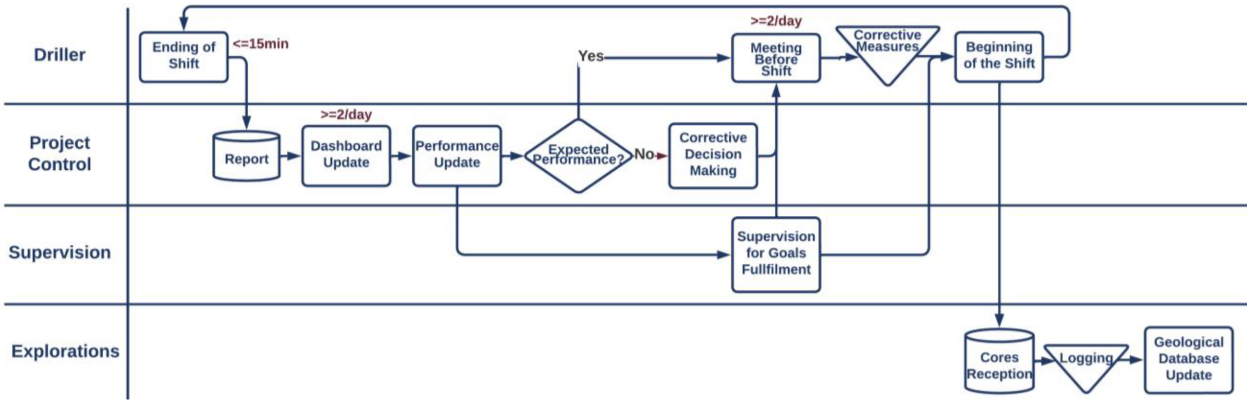

Figure 7: Work Process with VDC

Proposal Validation

The project specialists validated the proposal: the exploration director, general superintendent, project superintendent of the mining company, and the operations manager of the drilling company. Each one of the project specialists was interviewed to obtain their feedback.

VDC Objectives

The specialists stressed the importance of complying with the exploration department's decision and preventing the drilling team from focusing only on the meters drilled. This could lead them to increase the drilling speed to meet a physical progress goal.

PPM

The experts agreed that increasing production by mitigating the previously identified sources of variability was a viable alternative for meeting the objective.

ICE

The specialists agreed and supported disseminating the ICE sessions held during the on-call sessions. Previously, the agenda of these sessions was the distribution of information on the work to be performed during the on-call period. With the implementation of the ICE sessions, information began to be shared with all involved, and decisions began to be made during the sessions. The main topics of these sessions were the measures to be implemented to lower the variability shown on the dashboards from the VDC component.

BIM

Before starting the VDC implementation, the stakeholders witnessed the initial development of the dashboards, as shown in Figure 8. They showed interest in them, even requesting their distribution to know the project's status. Once implemented, they were aligned with the current information integration system.

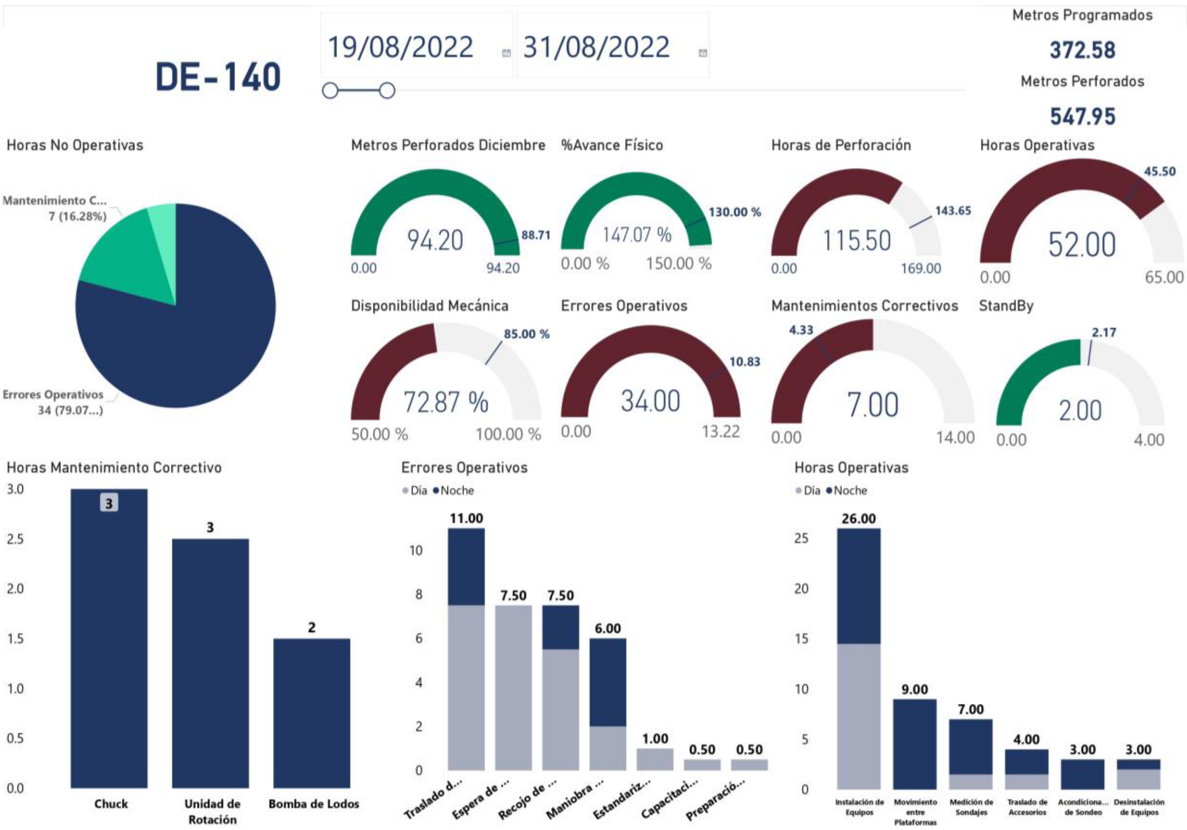

Figure 8: The dashboard for the integration of information

Client's Objective

The client's target of completing the project with 13,278.06 meters of core was surpassed, finishing the project with 15,794.20 meters drilled, which is 18.95% above the target.

Project's Objective

The project's target of 14.606.87 meters of core drilled was also surpassed by 8.13% above the target.

PPM, ICE and BIM

The results of the PPM, ICE, and BIM production objectives are shown in Table 1.

Table 1: PPM, ICE and BIM production objectives

Components	Production Objectives	Objective	Result
PPM	$\frac{Corrective\ Maintenances\ Hours}{Drilling\ Hours} x100\%$	<=10%	9.61%
	$\frac{Operational\ Delays\ Hours}{Drilling\ Hours} x100\%$	<=10%	18.31 %
	$\frac{StandBy\ Hours}{Driling\ Hours} x100\%$	<=10%	9.03%
BIM	Time for the receiving of drilling reports	<=15min	9 min
ICE	$\frac{\#Fullfilled\ Proposals}{\#Received\ Proposals} x100\%$	=100%	100%

As shown in Figure 9, the DE-140 drilling rig drilled 2,349.35 meters, exceeding the goal by 6.79% the 2,200.00 meters goal and abiding by the explorations department's order, while the DE-130 drilling rig only exceeded its monthly goal by 0.05% (Figure 10). Both DE-140 and DE-130 drilling rigs worked simultaneously during September 2022.

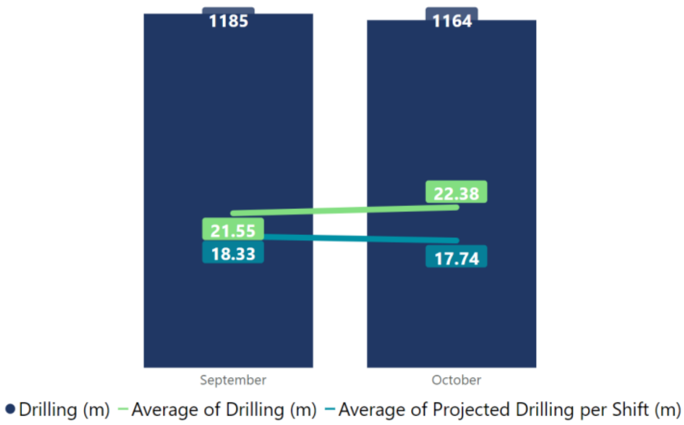

Figure 9: DE-140 drilling rig performance

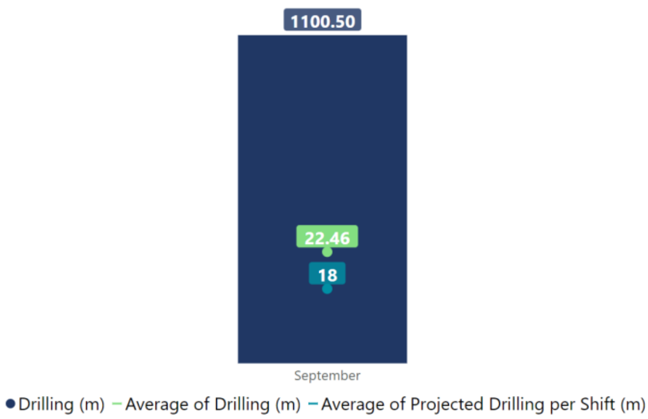

Figure 10: DE-130 Drilling rig performance in September

VDC implementation on this project focused on time optimization. With the identification of each variability source, the project stakeholder discussed and proposed improvement measures during ICE sessions to reduce those sources of variability. Some of the proposals received during ICE sessions were related to integrating stakeholders, and some were related to increasing staff. Considering that some proposals demanded an increasing budget, they had to be revised and analyzed.

CONCLUSIONS

The VDC implementation helped surpass the client's and project objectives as well as the ICE, BIM and PPM objectives except for the operational delays vs. drilling hours one. Although the drilling campaign was projected to be completed above the minimum target due to the performance in the first 5 months, the DE-140 drill rig, which was the subject of the investigation, managed to exceed its target by 6.79% for September and October 2022. The main difference in conditions between the two machines is the number of drilling hours achieved, with the DE-140 machine having a total of 319 hours of drilling and the DE-130 machine a total of 260 hours, equivalent to a 23% difference between both machines, which allowed that, despite the presence of the sources of variability, the DE-140 drilling machine achieved a higher production since its sources of variability were identified and controlled.

It can be concluded that the implementation of the VDC methodology was successful, with the DE-140 drill rig having shown higher production compared to a similar rig under the same conditions. In addition, compliance with the VDC production objectives indicates adequate project progress toward the client's and project objectives.

Finally, further investigation could be carried out considering the automation of entering information into the database and digitalizing the drilling reports.

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WORKLOAD LEVELING METRICS FOR LOCATION-BASED PROCESS DESIGN

Vishesh V. Singh[1], and Iris D. Tommelein[2]

ABSTRACT

Process design can help to meet project deadlines and ensure a smooth workflow. While work structuring (WS) is commonly used to design processes as linear flows, doing so may not account for 2-dimensional spatial variation in work and such variation can disrupt the flow. To limit disruption, takt production and the Work Density Method (WDM) have been developed, but metrics are yet needed to gauge and visualize the quality of workloads to achieve the desired flow. This paper presents multiple perspectives to assess desired outcomes of workload leveling and formalizes them into optimization objectives. It proposes nine metrics, grouped into seven types, to measure the success of achieving these objectives. The value of these metrics is illustrated using XLWoLZo, an Excel-based tool with an off-the-shelf genetic algorithm (GA), to solve a toy problem. The paper compares XLWoLZo's results obtained with the suggested metrics to the results of the metric used in existing models, examines how the resulting values of metrics compare to one another, and assesses their impact on desired outcomes. The paper concludes that no single "best" metric exists and suggests combining metrics to balance conflicting objectives. Finally, the paper discusses limitations and offers future research directions.

KEYWORDS

Process, Location-based planning, Takt planning (TP), Flow, Variability

INTRODUCTION

Process design (aka. process planning) matters to scholars and practitioners engaged in work structuring (WS) and production system design (e.g., Ballard et al. 2001a, 2001b). The aim is for process- and operation design to be aligned with product design. WS includes designing the "chunks" of work to be assigned, deciding their sequence and their release from one production unit (PU) to the next with or without decoupling buffers, and scheduling when they are to be done. A work chunk is "a unit of work that can be handed off from one production unit to the next" and a PU is "an individual or group performing production tasks" (Tsao et al. 2000). Thus, process design includes deciding what steps to include in a process, determining what work to assign to each step and who will do what, sequencing steps, and defining handoffs between them. In addition, it includes deciding what- if any buffers are needed between processes.

WS is commonly used to define construction processes as linear sequences of steps, thereby abstracting them to resemble line flow systems (e.g., manufacturing assembly lines). This abstraction can also be useful when studying the flow of crews. However, construction

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processes have work that depends on the 2-dimensional (and 3-dimensional) spatial characteristics of the project. Ignoring spatial variation of work can affect the quality of the assumed linear flow.

Location-based methods including takt production (aka. takt- or takt-time planning and control) (e.g., Bulhões et al. 2005, Fiallo & Howell 2012, Frandson et al. 2013, 2014, Haghsheno et al. 2016, Lehtovaara et al. 2021, Tommelein 2017, Theis et al. 2017) emphasize concern for space use in production system design. In the planning part of takt production, the aim for process design is to designate zones (work areas or locations) on a construction site where crews will work successively, one at a time, and complete the work in their step within a fixed amount of time (called the takt). The desire to plan work in different zones to a takt is difficult to satisfy because the quantity and complexity of construction work, and consequently the time needed to do that work, tends to be distributed non-uniformly in space.

To characterize non-uniformity, location by location, of the time needed by trades to complete their work, Tommelein defined the concept "work density" and developed a planning method based on it, called the Work Density Method (WDM) (Dunnebier et al. 2014, Tommelein 2017). The objective of the WDM "is to create one-piece process flow based on space use by zone, with the handoff being a zone and occurring at specified points in time" (Tommelein 2022). The WDM describes a numerical way of zoning a workspace while minimizing the workload peak across zones and steps to meet the desired takt (Jabbari et al. 2020, Tommelein 2022). In contrast in this paper, we view workload leveling from multiple perspectives, not only that which aims to reduce the workload peak. We identify metrics that measure, describe, and visualize the "levelness" of a workload, and accordingly define workload leveling.

The next section of this paper reviews literature on process design specific to takt planning, flow, and the WDM, and literature on a problem that is somewhat similar to workload leveling, namely resource allocation and leveling for construction scheduling. The section thereafter introduces desired outcomes of process design and suggests metrics to be studied as performance indicators towards achieving these outcomes. A section on research implementation presents the computer-based tool developed using an off-the-shelf genetic algorithm (GA) to optimize a toy planning problem so that the results from the optimizations according to the suggested metrics can be evaluated and discussed. This paper concludes with recommendations for metrics to enhance process design methods and suggests future research.

LITERATURE REVIEW

TAKT PLANNING AND FLOW

Construction project management has traditionally focused on transformation at the activity level, ignoring handoffs between activities (Ballard and Howell 1998). In contrast, Koskela (2000) acknowledged that transformation-, flow-, and value views on production systems are complementary and must be considered together to improve production more holistically. Therefore, and among other things, flows must be identified and measured.

Given that most construction activities have varying durations and work spread out unevenly in space, it is difficult to identify workflow. Irregular and erratic workflow translate into incomplete work and untimely hand-off of space. Process design with workflow in mind must ensure that the scope of work is well defined by process step and location so that the assigned work can be completed and handed over within the allotted time. Spatial continuity and timely completion tend to reduce the share of non-value-adding activities and reduce the degree of control complexity (Alves and Formoso 2000).

The term workflow has been widely used in the Lean Construction literature, but different authors have used it to refer to different types of flows. Among them, Shingo (1986) described production in terms of two types of flow: process flow and operation flow. Processes represent what happens to raw materials (and pieces of information) as they flow through the project and become finished goods, with work done stepwise by different crews. Operations represent what people with tools and equipment (referred to as crews or production units) do to products. Tommelein et al. (2022) differentiated flows in construction from a location-based planning perspective while recognizing their two-dimensional nature. They defined process location flow as synonymous with process flow and trade location flow synonymous with trade flow.

Process flow determines how long it will take to get a product to the customer. This duration is called the process cycle time and it relates to the system's speed (aka. throughput rate). Since a process comprises steps of work performed by crews, the durations of these steps (the step cycle time or workload) define the throughput rate. An objective of production system design is to match its throughput rate to the customer's demand rate (Hopp and Spearman 2011). The maximum amount of time allowed for producing a product (supply rate) so that it will meet the customer's need is called the takt. Using takt planning, a process can be designed so that each step of work can be completed reliably within the allotted time by crews following each other sequentially while going from one zone to the next.

The literature on flow and methods for takt planning in construction (cited previously) highlight different perspectives on what is considered a good takt plan. They consider process flow as well as trade flow and other flows, and trade-offs between them. The WDM for example (described next) allows planners to objectively balance process flow with trade flow.

WORK DENSITY AND WORK DENSITY METHOD (WDM)

To improve the quality of production plans (e.g., takt plans) in terms of achieving a shorter duration and higher workflow reliability, a goal is to reduce variability in the system. In construction processes this can be done by standardizing work, instilling regularity of work location and timing, and defining clear hand-offs between crews, thereby reducing the requisite amount of control and coordination between them.

Rather than zoning a work space by simply dividing space according to physical features of the structure being built, the WDM performs both workload leveling and zoning. The idea is to define zones so that number of work hours are similar for all steps of trades moving from one zone to the next (Frandson et al. 2013). Specifically, the WDM defines zones while minimizing the peak workload across all zones and all trades.

For a given work scope and trade crew working in a certain unit of space, and associated work structuring specifics, "work density" describes the unit of time the crew will need to complete that scope. Work density captures what work will be done, by whom, where, and how (Tommelein 2017). For projects with repeating architectural features in their product design (e.g., modular hotel rooms), planners can define Standard Space Units (SSUs) (Binninger et al. 2017) and repeated reliable handoffs of more-or-less similar workloads to be completed within a takt. Even for projects without such architectural features, i.e., where handoffs of similar workloads are not obvious, Jabbari et al. (2020), Singh et al. (2020), Diab and Tommelein (2020), and Tommelein (2022) were able to apply the WDM as the method takes as input a work density map for each step in a process. The map represents how much time the crew will need to complete their work across the work space, granularized cell by cell. Tommelein (2017) and Singh et al. (2020) detailed processes for creating work density maps.

The WDM supports process planning for a linear sequence of steps (a process) using a work density map for each step. Work space is divided into zones (that are mutually exclusive and collectively exhaustive) by assigning cells from work density maps to each zone. Then, step by step, the work densities of cells in each zone are added. The resulting cumulative work density, called the step cycle time or workload, describes the time a crew needs to complete their step-worth of work in the given zone.

The workload distribution across zones and steps visualized on a workload histogram or Yamazumi chart helps planners see if a given process design meets their desired outcome(s). If not, the planner may use various throttles (e.g., changing zone boundaries, modifying process steps, changing resources or means and methods available to the crew) to modify the plan. The characteristics that make for a desirable process plan can change with the situation and may require trade-offs. For example, a common trade-off in location-based methods involves reducing the time 'workers wait on work' (crew flow) versus 'work waiting on workers' (process flow) (Linnik et al. 2013).

RESOURCE LEVELING IN CONSTRUCTION PROJECTS

The workload leveling problem is similar to resource leveling and resource-constrained project-scheduling problems (RCPSPs). Resource allocation methods ensure that resources required for a plan do not exceed resource availability constraints (e.g., Colak et al. 2006, Davis 1974, Liu et al. 2005). Although in the basic RCPSP model reduction or minimization of the project duration remains the single most studied objective, several extensions of RCPSP consider other objectives or combinations thereof, such as variabilities in the project environment and resource capacity (Chakrabortty et al. 2017, Hartmann and Briskorn 2010).

Some resource leveling methods try to reduce fluctuations in the number of resources used, while others strive for continuous use of resources to improve productivity and reduce cost (e.g., El-Rayes and Jun 2009, Hegazy 1999). The mathematical formulation of these methods may use one or multiple objectives similar to workload leveling, i.e., to minimize resource fluctuations or lower resource peaks. Examples include the minimum moment method (Harris 1978), the PACK method (Harris 1990), the double moment method (Hegazy 1999), and the entropy maximization method (Christodoulou et al. 2010).

Since these methods are typically used in transformation-based optimization models (exemplified by the Critical Path Method (CPM)) (Brucker et al. 1999), the differences with flow-based process planning methods (exemplified by the WDM) must be highlighted. Resource allocation methods may prioritize critical activities over others when allocating resources. When multiple activities require the same resource, different methods may prioritize them differently. Resource leveling methods tend to prioritize the use of resources required for critical activities by scheduling those activities at their earliest possible time. They minimize resource fluctuations by shifting noncritical activities within their available float to keep the project duration of the original early schedule unchanged, if possible (El-Rayes and Jun 2009). In contrast, in takt planning, there is no prioritization for resource allocation or leveling as all activities (i.e., steps in a process) are critical. In that sense, steps within a process have no float. However, each step has a capacity buffer to ensure enough people on the crew are at the ready so that, in case work takes slightly longer than anticipated, they will be available and able to complete their step within the takt. In addition, takt plans include buffers between processes and at the end of processes. The judicious use of buffers prevents delays that could reverberate through the schedule (Dlouhy et al. 2019).

Flow-based planning methods are relatively new compared to the extensive body of knowledge that exists for transformation-based methods. A missing piece for their broader adoption pertains to metrics: there is a lack of metrics that characterize qualities of flows. In the next section, we discuss objectives and desired outcomes for location-based process design methods, and we then propose several workload leveling metrics.

WORKLOAD LEVELING

OBJECTIVES AND DESIRED OUTCOMES

In lean production, takt plays a key role in synchronizing processes and operations. The workload for a step in a given process may be less than, more than, or equal to the takt imposed by the customer on the process. By matching workloads to the takt, planners can eliminate waste, such as waste stemming from unevenness and overburden (Frigon and Jackson Jr. 2009). In construction, this is done (1) at the strategic level to meet the project deadline and (2) at the operational level to meet phase- or process milestones and objectives such as generating evenness in workflow and avoiding trade stacking.

Workload leveling tries to achieve a steady flow of work for processes, trades, crews, etc. With that said, to define metrics that measure success towards achieving these outcomes, we first define desired outcomes:

O1. Meet customer deadline (phase/process duration) by meeting the customer's takt or by reducing the duration by increasing concurrency.

O2. Achieve constant crew size (Ballard and Tommelein 1999) by reducing the variation of workloads across zones, thus improving trade (location) flow (Sacks 2016).

O3. Increase worker utilization (reduce the time workers wait on work) by providing timely hand-offs of zones and reducing the need for inter-trade coordination.

O4. Increase space utilization (reduce the time work waits on workers) by reducing the variation of workloads across steps in each zone and designing for spatial continuity (Alves and Formoso 2000), thus reducing overproduction waste (Linnik et al. 2013) and improving process (location) flow.

O5. Reduce workload variability by reducing the variation of workloads across steps and zones.

O6. Reduce process step variability by standardizing work and adding a capacity buffer (underloading) to an individual step.

We next identified metrics to measure success in achieving these outcomes.

METRICS FOR WORKLOAD LEVELING

To evaluate and compare the quality of levelness of workloads to meet the desired outcome of a process design, planners need metrics. Different planners may desire different outcomes and thus need different metrics. To accommodate trade-offs and gauge different outcomes, this paper suggests nine metrics, grouped into seven types as Metrics M2 and M4 each have two parts, a and b. These metrics are:

M1. Workload Peak is the maximum workload considering all steps and all zones. The objective is to minimize this peak. This metric is illustrated by the dashed red line vs. the tallest bar in Figure and 2.

M2. Average of Ranges is the average (aka. mean) value of the ranges of workloads, i.e., the difference between the maximum and the minimum workload, but workloads can be grouped in two ways:

M2a. Grouped by Zone: When workloads are grouped by zone, the range of workload is calculated for each zone, and then, the mean of ranges across zones is calculated.

M2b. Grouped by Step: When workloads are grouped by step, the range of workload is calculated for each step, and then, the mean of ranges across steps is calculated.

The objective is to minimize this range. This metric is illustrated by the gap between the solid red line and the solid green line in Figure and 2.

M3. Workload Range is the difference between the maximum and the minimum workloads across all zones and steps. The objective is to minimize this range. This metric is illustrated by the gap between the dashed red line and the dashed green line in Figure and 2.

M4. Range of Averages is the range of the mean workloads per zone or each step. The objective is to minimize this range. This metric is illustrated by the flatness of the purple line in Figure and Figure .

M4a. Grouped by Zone: When workloads are grouped by zone, the mean of the workloads for each zone is calculated and then the range is calculated between means for all the zones.

M4b. Grouped by Step: When workloads are grouped by step, the mean of the workloads for each step is calculated and then the range is calculated between means for all the steps.

M5. Peak to Average Ratio is the ratio of the maximum to the mean of workloads across all zones and steps. The objective is to minimize the ratio between the maximum and the mean of all workloads.

M6. Standard Deviation is the statistical property that measures how dispersed workloads are relative to the mean. The objective is to minimize this standard deviation. A low value means workloads are clustered around the mean. A high value means they are spread out.

M7. Moment is the sum of squares of centroids (= height/2) of all bars in the histogram, i.e., workloads across all zones and steps. The objective is to minimize the moment by reducing workloads or redistributing them.

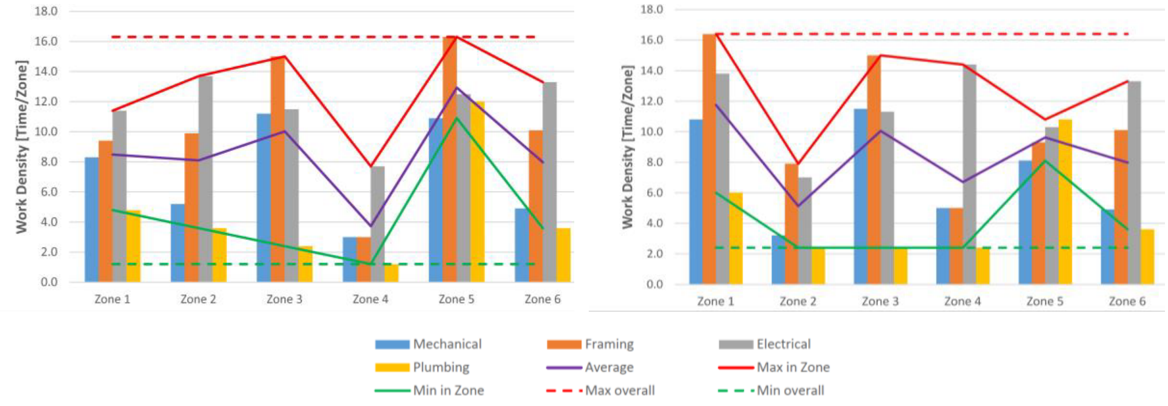

Figure 1: Workload histogram by zone for objective M1 (left) and objective M2b (right)

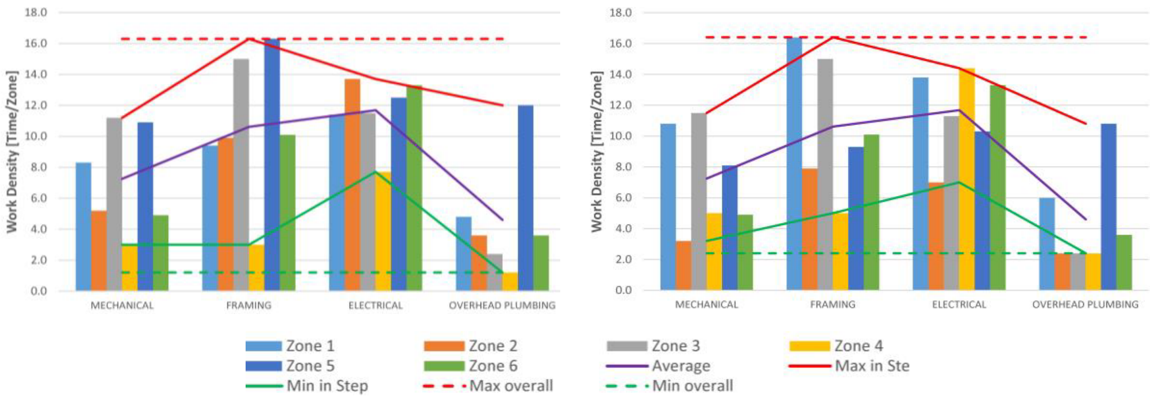

Figure 2: Workload histogram by step for objective M1 (left) and objective M2b (right)

Figures 1 and 2 illustrate the workload histogram after optimization using M1: minimizing workload peak (on the left) and M2b: minimizing the average of ranges grouped by step (on the right), grouped by zone and step respectively. To compare these metrics, we implemented an optimization tool and programmed the metrics as objective functions, as is discussed next.

MODEL IMPLEMENTATION

TOY PROBLEM

Using a GA-based model applied to a toy problem, we programmed the aforementioned metrics one at a time to be the objective function and ran the model to find the optimal solution. The toy problem includes work done by four different trade crews, namely (1) Mechanical, (2) Framing, (3) Electrical, and (4) Plumbing (Figure 3). As these crews are assumed to be working in a linear sequence, each crew's work density map represents a step in the process.

This problem stemmed from a pilot project conducted by Frandson and Tommelein (2014) and Dunnebier et al. (2014) and was also used to illustrate new planning methods including WoLZo developed by Jabbari et al. (2020) and GAWoLZo by Diab and Tommelein (2020).

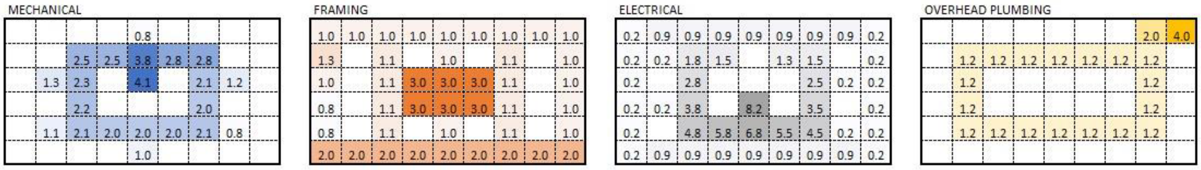

Figure 3: Work density maps for crews in toy problem (part of Fig. 3 in Jabbari et al. 2020)

EXCEL IMPLEMENTATION AND GENETIC ALGORITHM (GA) APPROACH

The toy problem was programmed as a Microsoft Excel based tool, called **XLWoLZo**, which stands for e**X**ce**L** **Wo**rkload **L**eveling and **Zo**ning. The optimization uses the off-the-shelf Microsoft Excel add-in called Solver, provided with the parameters and constraints for work density and zoning as input. The complexity and quality of the problem definition affect the Solver's ability to find a solution. In our case, the problem formulation includes a mixture of continuous decision variables (e.g., the work density in each zone for each step) and integer variables (e.g., zoning grid size). This makes it a mixed integer linear programming (MILP) problem.

In problem formulations where objectives and constraints are non-smooth and non-convex functions of the decision variables, and formulations that use Excel formulas like "IF", both of which are true for this problem, obtaining global optima is unlikely. For such problems, Solver Optimization Methods (2023) recommends using the Evolutionary method, a type of GA. This method provided a solution in a sufficiently short computation time (on the order of several minutes when running Microsoft Excel 365 (v. 1904) on an Intel Core i7-8550U CPU).

The constraints are that zones must be convex, non-overlapping, and non-empty. Recognizing the limitations of Excel to program complex constraints, XLWoLZo constrains zones to rectangles. For example, to divide the work space into six zones, the evolutionary solver first tries to draw a horizontal zone boundary (arrow 1 in Figure 4, where the boundary can be at the bottom of row 1, 2, 3, 4, or 5), thereby dividing the work space in two parts, and then for each part draws two vertical zone boundaries (arrows 2 and 3 at the top in Figure 4, and arrows 4 and 5 at the bottom) resulting in a total of 6 zones.

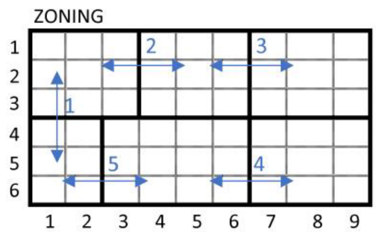

Figure 4: XLWoLZo zone boundary movements

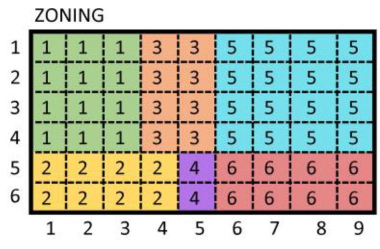

Figure 5: XLWoLZo solution layout for Z = 6 while minimizing workload peak (M1)

The GA moves the zone boundaries until it reaches a solution that it cannot improve upon (based on its convergence parameter or the pre-set computational time limit). Figure 5 shows the zoning solution reached for Z = 6 and the optimization objective set to minimizing the workload peak (M1).

XLWoLZo was run with each of the nine metrics as the optimization objective, one at a time. For each one, the resulting zoning layout and corresponding workload distribution, the values for all 9 metrics were calculated. The results were depicted in workload histograms grouped by zone (e.g., Figure 1) or grouped by step (e.g., Figure 2). Figure 1 shows, when the objective is M1, that the workload for Mechanical trade in Zone 1 is 8.3 time units. This value 8.3 is computed by adding the work density from the Mechanical work density map (Figure 3) for cells that are in Zone 1 (Figure 5). The results from these computations are discussed next.

DISCUSSION

WORKLOAD LEVELING MODEL COMPARISON

The toy problem was solved using WoLZo, GAWoLZo, and XLWoLZo with the number of zones ranging from two to six. In WoLZo and GAWoLZo, the objective was to minimize the workload peak across all the steps in a process according to the WDM (Tommelein 2022). Minimizing the workload peak typically results in minimizing the process duration, barring some exceptions (Jabbari et al. 2020). For XLWoLZo, the model was run 9 times, once for each of the 9 objectives.

As these three models impose different constraints on the geometry of zones, the results they obtain vary in zoning and, correspondingly, application of the metrics gives different results. XLWoLZo has the most restrictive geometrical constraints on zones and therefore produces results that are worse than those of the other two models. The WoLZo Model R divides the work space into rectangular zones, achieving its optimal value of 15.20 time units, which is 7.2% better compared to XLWoLZo's value of 16.30 time units. The WoLZo Model L and GAWoLZo allow non-orthogonal zone shapes and thus result in even better values, respectively 12.30 and 13.50 time units. Admittedly, the geometric constraints imposed by each of these models result in zoning layouts that may not be practical in real-world scenarios. Future research can focus on allowing other zoning geometries and better optimization algorithms.

COMPARISON OF NINE OBJECTIVE FUNCTIONS

Each of the 9 metrics, one at a time, was programmed to be the objective function in XLWoLZo. For each optimal zoning obtained, XLWoLZo also assessed the values of the 8 other metrics. E.g., when optimized for M1 (workload peak), resulting in M1 = 16.30 (Figures 1 and 2), the other metrics have as values M2a = 8.48, M2b = 9.58, M3 = 15.10, M4a = 9.20, M4b = 7.08, M5 = 1.91, M6 = 4.44, and M7 = 1101.88. Conversely, using each of the other 8 metrics as the objective function, resulted in M1's values of 24.30 for M2a, 16.40 for M2b, 16.30 for M3, 22.60 for M4a, 24.10 for M4b, 16.30 for M5, 16.40 for M6, and 16.40 for M7.

Numerically comparing results across all metrics per each objective, the scores for metrics **M2b, M6, and M7** (average of ranges grouped by step, standard deviation, and moment) performed the best in terms of also providing relatively good values for the other metrics. Metrics **M2a, M4a, and M4b** (average of ranges grouped by zone, range of averages grouped by zone, and range of averages grouped by step) performed the worst. Metrics **M1, M3, and M5** (workload peak, workload range, and peak to average ratio) fell in between.

Several metrics are clearly correlated.. M6 and M7 (standard deviation and moment) are both calculated as the product of a constant to the square of each workload and thus their result gives the same results. Standard deviation is not a square but is calculated using variance, which is dependent on the square of workloads.M1 and M5 perform similarly, as mathematically they are the same. Both functions are dependent on the peak, as the average calculated in M5 remains the same for any distribution of workload. This is true in the case of our implementation but can change if a throttle is used to change the underlying work density values (e.g., increasing crew size reduces work density). Strong correlation between metrics show they are interchangeable.

METRICS AND OUTCOME RELATIONSHIPS

In a real-world situation where multiple parties work with conflicting objectives, there is a need to understand the impact of the metrics on different performance outcomes. Balancing between different desired outcomes can be improved by understanding their relationship to the metrics being used to measure them. From the results of XLWoLZo, we observe that:

M1 measures workload peak. Lowering this indicates the possibility of lowering the takt and process duration. Assuming no variation, when M1 <= takt, the process will meet deadline (**O1**).

M2a measures the variation of workload across process steps in each zone. A lower M2a indicates better process (location) flow (**O4**).

M2b measures the variation of workload across zones for each trade or step. A lower M2b indicates better trade (location) flow (**O2, O3**).

M3 measures the variation of workload across all steps and zones. A lower M3 indicates reduced production variability(**O5**). It also improves process (location) and trade (location) flow, but its impact on either is lower than M2a and M2b as it is not biased towards either.

M4a and **M4b** indicates similar effect as M2a and M2b respectively but perform worse.

M5 indicates a very similar effect as M1, and both perform average.

M6 indicates a similar effect as M3 but performs much better due to quadratic versus linear relationships respectively.

M7 indicates a similar effect as M1 but performs much better due to quadratic versus linear relationships respectively. Due to its dependence on the square of workloads, it is reducing higher workloads more than smaller ones.

Takt planners can use capacity buffers to absorb process variability by underloading steps, e.g., to 70-80% of their capacity (Frandson et al. 2015). Thus, sizing of each trade's capacity buffer becomes part of the workload levelling process, as step cycle times need to be lower than the takt. Planners need to balance workers waiting on work (idle time), by providing timely hand-offs of zones, while also underloading to absorb variability. These metrics suggest a distribution of workload values, and with a given target takt, can be used to allocate capacity buffers (**O6**).

Reducing workload variation (by controlling underloading and overburdening) and keeping step cycle time below the takt (with a capacity buffer), results in (1) reduction in work (zones) waiting on workers (steps), in turn improving spatial continuity, and (2) reduction in workers waiting on work, in-turn suggesting timely hand-offs of zones. Achieving both results together is difficult however as one tends to counter the other. This was observed with metrics **M2** and **M4**, both of which are grouped by zone and step. When optimized for grouping by zone, the performance of grouping by steps is poor, and vice-versa.

General contractors (GCs) and trade partners have different priorities as they manage crews between a portfolio of projects. GCs tend to favor process (location) flow, whereas trades favor trade (location) flow, while both manage the related buffers (Frandson et al. 2015). To understand the trade-off between the two desired outcomes we can use a combination of metrics.

Solutions can be employed to deal with these effects, e.g., if a trade is greatly underloaded in specific zones, then the remaining time needs to be planned for the workable backlog, skill development, improvement studies, etc. Another way of understanding the interaction between these two sides involves visually reading the workload histograms. Typically, these histograms are generated with workloads of steps grouped by zones (Figure 1). This makes seeing the variation in workload distribution across steps in a zone easier as opposed to the variation between zones for a step. Thus, to better understand the visual implication of a metric on the workload histogram, we plotted them grouped by zones (Figure 1) and by steps (Figure 2).

To incorporate the trade-offs in real-world scenarios, further study of multi-objective optimization is in order. This may include pareto optimization or creating an aggregate objective function by assigning weights to objectives depending on their relative importance to define an.

We suggest incorporating several metrics on dashboards to support management decisionmaking pertaining to work structuring, zoning, crew sizing, etc.

CONCLUSION

This paper presented an overview of workload leveling for location-based process design using the work density construct, describing various desired outcomes and how they can be measured. Existing models use only the workload peak metric for process optimization. Using metrics described in the literature on resource allocation and leveling in project scheduling as a guide, the paper proposed 9 workload leveling metrics, including workload peak, average of ranges (grouped by zone and step), workload range, range of average (grouped by zone and step), peak to average ratio, standard deviation, and moment.

The identified metrics were programmed for a toy problem on Microsoft Excel (XLWoLZo) as the objective function for a GA to optimize. As expected, the results indicate that there is no single "best" metric for workload leveling. The choice of metric(s) will depend on a multitude of constraints and preferences from the physical site and the project team. Metrics merely provide a quantitative assessment to compare performance toward a desired outcome. Thus, the suggested metrics are later matched with common desired outcomes of location-based process design, and the choice of using a metric is left to the reader. Several objectives (**M1** and **M5**, and **M6** and **M7**) indicate similar outcomes and thus generate similar solutions. These can be used interchangeably and should not be used together when considering different perspectives. Instead, some metrics that indicate opposing outcomes (**M2a** with **M2b**, and **M4a** with **M4b**) should be considered for trade-offs. Overall results and their relationships with desired outcomes showed that metrics **M2b**, **M5**, and **M6**, though meant to measure performance for certain outcomes, can do their work while also balancing other outcomes.

For future research, these objectives can be incorporated into optimization models such as WoLZo or as metrics to support manual workload leveling and zoning using tools such as ViWoLZo. To incorporate the real-world trade-offs, further work may focus on pareto- or other multi-objective optimization, or show metrics on management dashboards for collaborative decisionmaking.

In summary, this paper provides insights into the selection of metrics for workload leveling in planning methods, and it highlights the importance of considering the specific context and objectives of the planning scenario when choosing a metric.

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COMPARISON OF TAKT PLANNING METHODS USED ON PROJECTS OF DIFFERENT TYPES

Iris D. Tommelein[1] and Jon Lerche[2]

ABSTRACT

Takt planning has been used to deliver projects of different types and in different industry sectors. We presuppose here that the methods used to develop project takt plans therefore must vary. To test whether this presupposition holds we consider two different project types (wind turbines and healthcare facilities) and compare sample projects of these types in terms of the rationale that was applied when developing their takt plans. We show that the rationale takes into account the relative cycle times and associated resource costs of individual steps in their production processes, considering the dependencies between those steps and between processes. Little has been written in the literature to date about the relative costs of process steps in takt plans, and how these costs affect the opportunities planners have and choices they make when leveling workloads to determine the so-called "operable" takt time. That is done here. This paper contributes to the literature on takt production used to deliver construction projects by describing theoretical concepts that help to differentiate takt planning methods used to plan projects of different types.

KEYWORDS

Production system design, takt production, takt planning, work structuring, flow, complexity, cycle time, cost, Critical Chain, Theory of Constraints

INTRODUCTION

Takt planning has been used to deliver construction projects and phases of work within projects of different types and in different industry sectors, such as multi-family housing, healthcare, and manufacturing plants. Project types can be differentiated based on characteristics such as their complexity, size, spatial features (e.g., location, horizontal vs. multi-story, onshore vs. offshore), and supply chain ecosystem (e.g., supplier and subcontractor availability and capability), and phase types can be differentiated likewise within projects. Recognizing variation by project- or phase type, one might expect that methods used to develop project takt plans will vary. This expectation is in line with Shenhar's (2001) argument that "one size does not fit all projects," i.e., that different types of projects should be managed in different ways. While Shenhar (2011 Table 1) labels all construction projects as "build to print" and lumps them together in the Low-Tech bin, within this bin further distinctions can certainly be made. With this in mind, we start this paper from the presupposition that the methods used to develop project (takt) plans therefore must vary.

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To test whether this presupposition holds we consider two different project types, namely wind turbines and healthcare facilities, and compare sample projects of these types in terms of the rationale that was applied when developing their takt plans. The rationale is based on relative cycle times and associated resource costs of individual steps in their production processes, considering the dependencies between those steps and between processes. To ground this paper's contribution in prior work, we next review literature related to takt production used to deliver construction projects, and scheduling-related topics including the Critical Chain method (CC) based on the Theory of Constraints (ToC). We then explain the perspective we adopted for our analysis, that considers the relative costs of process steps in takt plans, and how these costs affect the opportunities planners have and choices they make when leveling workloads to determine the so-called "operable" takt time. That section is followed by the presentation of Project Type 1, a wind farm infrastructure project, and Project Type 2, a healthcare facility project. Each one includes a description of the rationale applied in planning these projects. The paper ends with a discussion and conclusions.

LITERATURE REVIEW

PROCESS STEP DEPENDENCIES AND INTER-PROCESS NETWORK DEPENDENCIES

Before talking about process steps in takt plans, it is worth separating the functions of planning and scheduling. According to Kelley & Walker (1959), planning is defining what activities have to occur and their order of occurrence based on technical or logical relationships (the topology of the network); scheduling further adds the dimensions of time and cost to these activities (the geometry of the network). The critical path method (CPM) highlights the sequence(s) of activities having the longest duration. A CPM schedule does not depict the possible occurrence of variation in duration or timing of activities, or the existence of alternative activities. A manifestation of variability (e.g., uncontrolled stoppages) may result in delaying the project.

Since the inception of CPM, a variety of other and often-times related network scheduling methods have been developed (e.g., Russell & Wong 1993). Location based scheduling (LBS) explicitly depicted location-dependent logic (Willis 1998, Harris & Ioannou 1998, Kenley & Seppänen 2010, Lerche et al. 2019). Takt planning further introduced into the plan a given beat (the takt) and the direction of the flow of work, as will be elaborated on in the next section. The Critical Chain (CC) method with its drum-buffer-rope concept defined the slowest process step as the drum and based on that drum paced the other process steps (Goldratt 1999).

Whether to use CPM, LBS, Takt, or CC as methods for planning needs to be decided judiciously in order to match the project requirements and opportunities provided by their context. Any one or several of these methods can be used within the Last Planner® System (LPS), where the work structuring of activities is based on principles applied to logical layers of planning (Ballard 2000, Ballard & Tommelein 2021). LPS focuses on how to plan in light of what to accomplish with the plan, rather than on the specifics of what a plan consists of (Lerche et al. 2020b). The LPS does not single out the use of any method in particular.

When scheduling, activities are aligned according to their technical or logical relations. Howell et al. (1993) defined these as degrees of linkage (from loose to tight) between processes. Hopp and Spearman (1996) found these linkages to have dependent or independent demands. Bølviken et al. (2015) defined relationships between processes as dependencies that can turn into constraints, either physical or non-physical. For example, a physical constraint arises when a component or prefabricated unit's physical characteristics (weight, dimensions, etc.) exceed the crane capacity (e.g., Taghaddos et al. 2018). Protecting the schedule (or production plan) from variability requires the discipline of actively removing or limiting such constraints (e.g., through work structuring and make-ready planning when using the LPS).

Using CPM, buffers may be introduced within and between activities to allow time or resources to mitigate the risks of being delayed from such constraints. LBS further allows for location buffers, and CC looks to create a buffer of inputs needed by the drum. Goldratt (1999) defines a system constraint as what prohibits the system from achieving higher performance, something that is not an act of God and can therefore be handled. This could be true for example in case of the crane, but then raises the questions "What are the tradeoffs?" and "At what cost?"

TAKT PLANNING

Researchers have described theoretical constructs and applications of takt planning or, more generally speaking, takt production (e.g., Frandson et al. 2013, Linnik et al. 2013, Binninger et al. 2019, Gadbois et al. 2018, Lehtovaara et al. 2020, Jabbari et al. 2020). As is presupposed here, takt planning methods will differ as the project types differ but research in this area is lacking. Barring exceptions such as Tommelein's (2022) detailing of the Work Density Method (WDM), we have found few papers that actually spell out the specifics of any method used to develop the takt plan. Nevertheless, at heart the methods include the following procedural steps:

1. Identify a sequence of steps that make up a linear process. Alternatively, linearize a process that has concurrent steps by sequencing its steps so that they have a one-on-one finish-to-start relationship with at most one other step, or by performing concurrent steps off-takt, that is, removing them from the process under consideration. To illustrate, each square in Figure 1 represents a process step and its color refers to a specific trade. One trade may perform different steps in the process either with the same crew or with different crews.

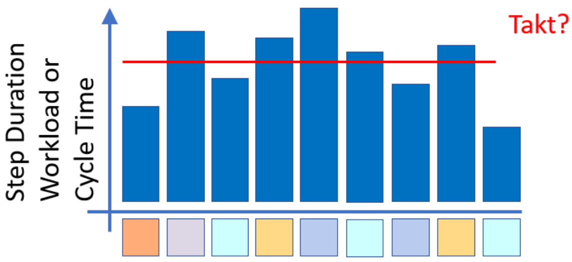

Figure 1: Workload histogram for a linear process
(aka. cycle time histogram or Yamazumi chart)

2. Based on the demand for the process deliverable, calculate what the takt should be (shown by the red line in Figure 1). "Takt Time [is] the pace that exactly meets customer demand given available production time. This is a customer-focused metric" (Moran 2022).
3. Determine the duration of each step. This duration is called the workload or cycle time. It is shown in Figure 1 by a blue vertical bar for each step.
4. The peak of all steps' cycle times must fall below the takt or the process will not be able to fulfil its customer's demand. That peak defines the "Operable Takt Time [which is] the pace you can actually achieve with your current process and equipment. This is a manufacturing-focused metric."[3] (Moran 2022).
5. If the operable takt exceeds the customer's takt, then lower the blue vertical bars until they all fall below the takt (red line). The difference between the two serves as a capacity buffer needed to absorb duration variability. Protecting the takt plan from variability is commonly

[3] Jabbari et al. (2020) used the notation T(Z) to refer to the peak workload in a workload histogram. This peak defines the operable takt time of a process, although they did not use that term. Z is the number of zones (locations where work is done) into which the work space is divided. T(Z) is a function of Z because the operable takt depends on how the workspace is divided into zones due to the fact that workloads may vary by trade and by zone.

done by underloading resources (i.e., creating a capacity buffer) or by allocating time- or space buffers (Frandson et al. 2015).

A blue vertical bar (including the tallest one called the peak workload that defines the operable takt) can be lowered by adjusting one or several “throttles” or “adjustment mechanisms” (Binninger et al. 2017) available to planners in general, namely: (1) Modification of product- and component characteristics, (2) Use of alternative breakdowns of the scope of work, (3) Resequencing of work and addition or removal of work from a process sequence, (4) Selection of alternative means and methods used by a trade, and (5) Development of worker- and crew trade skills, and selection of the number of trade resources that can be assigned.

Such throttling can make use of lean methods, such as:

- Single Minute Exchange of Die (SMED): a method to reduce changeover and exchange times between different components in a manufacturing setting. Some people spell out this abbreviation as Simplify, Move, Eliminate, or Delegate.
- Sort, Straighten, Shine, Standardize, and Sustain (5S): a method to increase work space efficiency.
- Plan Do Check Act (PDCA) aka. the Shewhart- or Deming cycle: a method for action learning, which in this context may be used to understand the conditions of process steps relative to each other. Workload leveling between process steps while aiming to achieve the takt (as is illustrated in Figure 1 with the red line) will require changes in cycle times: some will need to be reduced whereas others could be increased and still fall below the takt.

THEORY OF CONSTRAINTS

An alternative to using a method for takt planning is to apply the Critical Chain (CC) method based on the Theory of Constraints (ToC) (Goldratt 1999). The ToC starts by recognizing the slowest step (bottleneck) in a process. The bottleneck is designated as the drum or pacesetter for the process. Steps upstream of this bottleneck are paced using a pull mechanism called a rope that is tied to the drum. A buffer is intentionally built up before the bottleneck to prevent that bottleneck from starving. This explains the drum-buffer-rope method.

The drum-buffer-rope method can be applied to construction settings. However, its shortcomings must be addressed as well. Roser (2014) mentioned two. First, the rope ties the steps upstream of the bottleneck to that bottleneck, but the ToC is silent about how to manage the steps downstream. These downstream steps—like all other steps in the process—must be considered in any production system’s design. Second, a process may have, not one, but multiple bottlenecks and those may shift over time (Roser et al. 2002).

Lerche et al. (2022a) illustrated how a combination of takt and kanban thinking could be applied to protect the process steps deemed bottlenecks. The kanban (like the rope in the ToC) adds a pull link between process steps in the takt plan to prevent any process step from commencing when its preconditions are not met, or the previous task is not finished.

COST

As mentioned, an objective in takt planning is to make the operable takt less than the customer’s takt and this is done by lowering workload peaks or using other throttles. An issue not previously discussed is that the application of a throttle has not only cycle time- but also cost implications. When looking at only direct costs, in certain situations it may be reasonable to claim that there is no extra cost for using the throttle of speeding up or slowing down work. For example, assume that the cost to perform a step with a certain quantity of work (e.g., 60 units in a zone) can be computed by multiplying a production rate (e.g., one worker can install 5 units/hour) by the number of resources at their cost rate (e.g., a worker is paid $100/hour) (or some other function, but ignoring any non-linearities in the cost function that may arise for example from overcrowding). Using these example numbers, the duration of the step when performed by one worker is 60 units / (5 units/hour) or 12 hours and thus the cost of the step in this zone is $1,200. Using two workers, the duration is cut in half to 6 hours but the cost is still $1,200. Other considerations come into play in the throttling process especially when considering cost, such as:

- A cost penalty will be incurred when the workload is highly variable and unevenly distributed from one zone to another, as this makes it difficult for a trade to maintain a constant crew size. This is not to say that crew sizes cannot change over time, but it is the case that keeping people working together for a longer time results in better performance.
- Some workload variability could be absorbed by engaging multi-skilled workers, but they are likely paid more than less-skilled workers.
- Some resources are very expensive compared to others and may be available only in limited numbers. Throttling up may therefore be cost prohibitive or impossible altogether.

RESEARCH PERSPECTIVE

The research method follows a case study approach with multiple embedded units of analysis. The first unit of analysis is the case description in terms of context, process, and cost drivers. The second unit of analysis investigates the takt planning method as previously described with procedural steps 1 through 5.

PROJECT TYPE 1: WIND FARM INFRASTRUCTURE

PROJECT SCOPE

The construction of wind farm infrastructure combines multiple technical modules, to result in a power plant with a life time exceeding 20 years based on the turbines' end-of-life expectancy. Wind farms are often divided in two systems: (1) the transmission system (housing of electrical power transmission equipment or cabling) connecting the power plant with a national grid, and (2) the power generating system (cable connections, wind turbine generator structures) harvesting the wind's energy. The module assembly strategy follows what Peltokorpi et al. (2018) calls "sectional," leading to interfaces having clear technical dependencies.

PROCESS

As the wind energy industry is rapidly developing both onshore and offshore, modules are increasing in power output capacity and physical size (Enevoldsen and Xydois 2019). At the highest level, a wind farm can be broken up into separate packages, pertaining to grid connection points, cables, transformer stations, foundations, and wind turbines. Each of these packages then contains sub-systems or modules, e.g., the wind turbines package consists of the tower, nacelle, and blades. Lerche et al. (2022) revealed how the process time for an offshore cable termination is related to the design choices made not only for the cable itself but also for its support structures. They reported how the offshore wind farm infrastructure is assembled in accordance with its technical dependencies, and noted that technical dependencies appear to make the ordering of processes predictable and replicable. This is the case especially for installation processes that require equipment (e.g., cranes, purpose-built vessels, or underwater robotics) (Barlow et al. 2018), which might explain why offshore installation in particular has been planned using CPM (Lerche 2020). When a technical dependency is broken, schedule adjustments can be made, e.g., if a foundation is installed but cabling is not complete, the turbine can be installed but not commissioned, and temporary power generators would be required to sustain its product integrity (lifetime expectancy) until the cabling is completed.

Cost

The tradeoffs made by the infrastructure developers are related to the cost of installation versus the cost of maintaining power production, while accounting for the financial incentives for finishing early or at least on time that stem from the opportunity to start generating power and earn revenue (opportunity cost). Sovacool et al. (2017) described the difference between onshore and offshore in terms of the risk associated with the cost of the equipment, in particular purpose-built vessels used for offshore installation (Barlow et al. 2014). Installation vessels being the main cost driver, with an average rate of €250,000/day, has made both developers of offshore infrastructure and their supplier pool of manufacturers (cables, transformer stations, foundations, and turbines) conscious of vessel capacities and costs. Consequently, they have shifted their focus to limiting the time spent offshore (Lacal-Arántegui et al. 2018; Lerche et al. 2020, 2022). Although onshore wind farm infrastructure development and project execution use less expensive equipment, the relative cost of equipment is still considerable.

Defining the Takt

The technical dependencies provide clear direction for the linearity of process steps between trades. Wind farm infrastructure installation requires only a few trades, electrical and mechanical trades being the primary ones, where specialized resources for specific process steps are seen as 'off-takt'. Lerche et al. (2020, 2022) defined process steps according to module type and trade required (Figure 2):

1. For the main module process steps where the use of highly specialized equipment is essential (e.g., a crane with exceptionally large reach or hoisting capacity), these can be determined by contractual terms for either the equipment or for the assembly crew. It could also be determined by what durations to handle given modules are practically feasible for the equipment. Process steps preceding and succeeding these then either align with the drum (as mentioned in the ToC) or planned to a different takt. For process steps without such equipment requirements, the durations could be organized according to location or trade as is the case when developing a (takt) plan for building construction (Lehtovaara et al. 2020).
2. Considering large equipment for handling the modules (installation processes here) to be the drum, this sets the takt for up- and down-stream process steps. The takt is then calculated according to the beat of procedural step 2. Lerche et al. (2020) found that installation vessels set the beat, providing pre-assemblies with a turnaround rate that could be divided by the number of modules in a batch. Such a calculation would also apply in case additional units of large equipment (e.g., purpose-built vessels) are introduced.

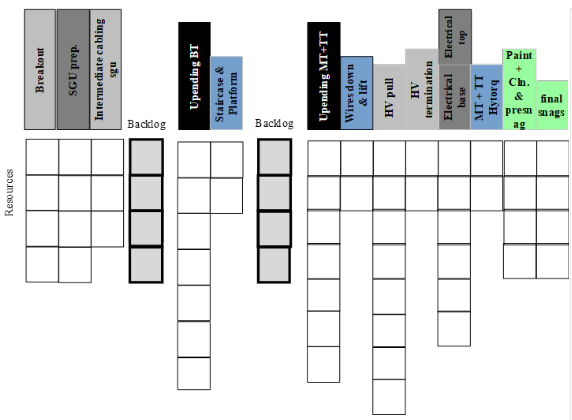

Figure 2: Process steps with resource requirements (Lerche et al. 2022)

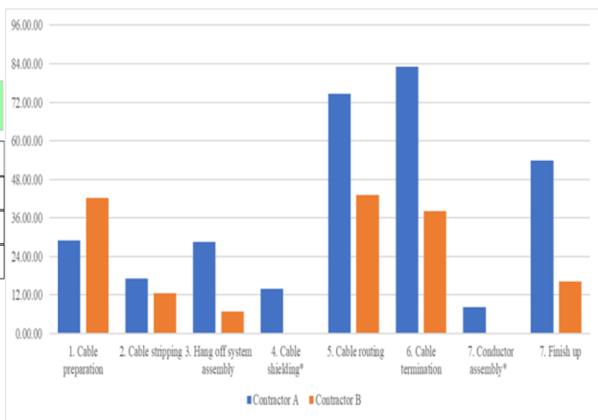

Figure 3: Comparison of process step durations between two contractors (Lerche et al. 2022)

3. Capacity buffering with resources allows for leveling the process steps durations, those process steps with high technical dependencies or equipment constraints require alternative solutions as design changes, or capacity improvements to the equipment. Simultaneous work of different trades is commonly used for offshore commissioning, allowing the trade to finish a location one at the time.

PROJECT TYPE 2: HEALTHCARE FACILITIES

PROJECT SCOPE

The construction of a healthcare facility comprises multiple project phases pertaining to the building's core-and-shell and fit it out (site work, foundations, structure, exterior cladding, interior rough-in, finishes, commissioning). Healthcare projects require the installation and commissioning of complex mechanical-, piping-, electrical-, fire-life-safety- and other systems each of which must meet stringent performance requirements (seismic safety, sustainability requirements, etc.), and all are packed together in a limited amount of building space designated to utilities. Therefore, these projects are considered complex when compared to commercial building or housing projects, for example.

Here, we focus specifically on a later phase of project delivery, namely interior work (rough-in and finishes), during which many trade specialists are involved. Because of interdependence between the trades' work, judicious coordination of that work can significantly help to speed it up. Therefore, not surprisingly, in healthcare- and laboratory projects such work appears to have been planned more often using takt (e.g., Linnik et al. 2013, Frandson and Tommelein 2014, Gadbois et al. 2018) than has been the case for earlier work (e.g., foundations).

PROCESS

Interior work is typically not dependent on a single, pacing resource (in contrast, e.g., structural steel erection may be paced by a tower crane). Due to its relative complexity, it is quite common to have ten if not more specialty contractors involved, all requiring access to and sharing site space, material hoists, as well as other resources. In addition to space and the aforementioned resource dependencies, the work of one trade often forms the substrate for the work of the next trade (e.g., framing must precede hanging drywall, priming, and painting).

For certain scopes of work, there is a natural flow to doing building construction work (Riley et al. 1995) and work will proceed in a Parade of Trades. However, that flow can be flexible: some work can be done out of order without becoming cost prohibitive. Dependencies exist but can be modified, e.g., while it is preferrable to paint walls before putting flooring in a room, if flooring needs to come first then protection can be added to avoid paint spilling on it.

COST

For each trade, the cost of an activity is a function of worker pay based on their skills, and the cost of materials, tools, and equipment (plus overhead and profit). Worker costs (as opposed to equipment costs in wind farm projects) are relatively high compared to the other costs. At the risk of overgeneralization, the resources required for healthcare project delivery are not as capital intensive as those required to deliver wind farm infrastructure.

Furthermore, the cost of work in a process, step-by-step, is relatively speaking commensurate across trades. To achieve schedule milestones, crews may be doubled up and work in different locations concurrently with no cost penalty (as explained earlier). Shared resources (e.g., material hoists and manlifts) may be expensive and scarce, but of note is that many trades take turns using them so that potentially many process steps are impacted by them (unless their use can be scheduled off-takt).

DEFINING THE TAKT

The customer process of rough-in and finishes, the commissioning phase, involves numerous systems (heating ventilation and air conditioning, potable and perhaps also grey water, medical gasses, building controls, etc.). Upon project turnover, the move-in phase involves getting people to occupy and use the building. The costs arising from missed handoffs between those processes and opportunity costs are high. A goal of takt planning therefore is to hit the project commissioning and turn-over milestone dates and to do so reliably.

DISCUSSION

UNDERSTANDING THE THROTTLES

Lowering of process-step cycle times can be done by applying throttles, as previously mentioned (also see Lerche et al. 2020, 2022, and Tommelein and Emdanat 2022):

1. Apply PDCA to reduce the cycle time of a process step (but do not confuse fundamental improvements with learning curve effects) as well as reduce its cycle-time variability.
2. Use technical solutions to reduce assembly durations, e.g., replace slower mechanical or hydraulic tools with faster electrical tools to shorten the duration of bolt tightening in module joints. Find alternative tool solutions to improve installation process steps (Zhao et al. 2018). Redesign work processes.
3. Crew up (or down) when worker availability is not a constraint (as may be when highly specialized workers are required, such as unique equipment operators) and sufficient work space is available.
4. Add equipment capacity to expedite work.
5. Divide process steps into smaller ones, esp. those with few technical dependencies and not requiring heavy equipment. E.g., if the crane is the drum, then try to remove steps that require crane use in order to alleviate its workload. Use a small crane for assemblies up to a defined height, before using the main crane for higher lifts.
6. Take some scope out of a process step and perform that scope at another time.
7. Pre-fabricate assemblies. As when working with larger modules being fabricated elsewhere, move assembly upstream from the construction site to a manufacturing site.
8. Design fewer process steps into the product, e.g., the cable case in Lerche et al. (2022).
9. Change the product design but be mindful that this can affect individual process steps positively or negatively (e.g., Figure 3 illustrates step durations of two contractors who completed similar processes but chose different designs).
10. Eliminate interface assemblies by "thinking in" the assembly process, e.g., apply mistakeproofing by using electrical plugs on both sides instead of hard wiring (e.g., Figure 4 in Tommelein 2008).
11. Add buffers to protect the bottleneck step in a process (i.e., ensure its efficiency and effectiveness), e.g., build up an inventory buffer of modules at quay side, ready for vessels to carry them offshore in order to protect the installation process step.

    Of note is that in the offshore literature there is a tendency to focus on the transport of personnel (Lerche et al. 2022), optimizing the use of vessels that are not directly involved in process steps (Petersen et al. 2016) and are not a process bottleneck. This practice merely reduces flow-variability but does not improve process performance.

Decisions in this regard must be made early enough to be most effective, however, even when made at the last minute they can still be beneficial to process performance.

IMPLICATIONS FOR TAKT PLANNING

Based on a project's type (Table 1) some throttles for takt planning are used more easily and cost-effectively than others. Steps for constructing wind farm infrastructure have numerous technical- and key resource dependencies; they involve expensive and unique equipment. As the dimensions of prefabricated units get larger, opportunities to devise alternative plans and flexibility in planning tend to diminish (you cannot beat physics). One runs into limitations on available equipment sizes and highly skilled operators, on allowable loads on bridges, overhead obstructions, ground pressures, allowable truck loads and volumes (weight per tire, weight distribution), etc. Equipment (the drum) determines the operable takt. It may be that one piece of equipment is available, but no additional one is readily available or affordable. In situations like this, planners must first resort to using SMED to improve drum throughput.

Table 1: Takt planning comparison

Case 1	Case 2
STEP IN TAKT PLANNING 1. Step and process definition: Dependencies define process step sequencing, Space, Steps in the process	
a. Dependencies express technical execution strategies. b. The dimensions of the modules determines the need for space (location), and what can be done in adjacent spaces. c. Requires fewer different trades (e.g., electrical and mechanical) with fewer and 'bigger' steps. It is clear who you need when and in what sequence.	a. Dependencies are based on choices related to logical sequencing of work, and there is some flexibility in that (e.g., paint walls before putting in flooring or vice versa, though the former may be preferred) b.. Work can be broken into "chunks" of various sizes which creates flexibility in deciding what to do where. c. Numerous specialist trades are needed and must coordinate their shared use of space (especially on 'fast' projects where concurrency can be achieved).
2. Customer takt	
Customer demand for speed is based on the business case but constrained by what is feasible given available equipment capacity (e.g., large vessels).	Customer demand for speed is based on the business case and drives the determination of production rates (quantity installed per crew hour) and resource loading.
3. Individual step cycle time	
Step cycle time may be on the order of hours, driven by equipment costs.	Step cycle time may be on the order of a fraction of one day to a few days, typically less than the time window covered in a weekly work plan.
4. Process operable takt	
Specialized equipment defines operable takt (and cost), i.e., drum (in CC). Lerche et al. (2020) revealed how the industry's tendency to focus on the drum beat defined by costly equipment.	Work density and resource availability defines operable takt (e.g., how many electricians can productively work in an electrical room?).
5. Process operable takt	
Protection of the drum by buffering with inventory (e.g., stage 2 or 3 times more modules than will be transported on any one vessel).	Use capacity buffering and workable backlog.

Planners can view processes from both a design- and commercial perspective. When engaged early in design they can balance these perspectives, whereas later that becomes increasingly difficult. When balancing is accomplished to the extent possible, they can design the takt plan based on the drum's beat and synchronize other process steps based on the drum.

In contrast to equipment-intensive work (e.g., foundation piles, segmented bridges, or wind turbine towers) that is dominated by the pace at which that equipment can "go," processes for healthcare project delivery have more substrate- and fewer technical dependencies. Worker-intensive work presumably has flexibility in crewing up or down. It is relatively easy to get more people and not too costly to provide the crew with needed tools and equipment.

Before construction starts, Case 1 has shown that actively thinking of repetition in design can be beneficial. Such repetition is also beneficial as the modules are prefabricated. Prefabrication means taking work out of a (site) process or moving work to another process in order to reduce a given step duration(s) and therefore the corresponding process duration. Case 2 can also benefit from prefabrication. In addition, Case 2 can benefit from designs that use multiple smaller components distributed in space, rather than a few larger ones focused in one area, when this leads to a decrease in work density by zone.

During construction, both cases benefit from conducting first run studies and designing operations, defining standard work, and mistakeproofing to help achieve reliability in step execution. While case 1 further can take advantage of repetition, it can further strengthen the effect from the other throttles, as the modules introduce limited variation. This also means that Case 1 can seek improvement through tool selection due to high repetitions, e.g., moving from slowly rotating hydraulic tool heads to electrical. Process step improvement for Case 2 relies on trades judiciously choosing the “best” trade tools.

Both cases reveal that increasing resource capacity can lead to process improvement, this is presumed easy for both cases, while Case 1 has a limitation of geographical space or work location constraints. Secondary around the resources, Case 2 also shows that scope of a step can be combined vs. divided and/or reallocated to other steps within limits of constraints imposed by numerous trade jurisdictions. As Case 1 dominantly require mechanic or electrical resources, the use of multi-skilled trades is possible, this is supported by the offshore settings being less restrictive in terms of labor union jurisdictions.

CONCLUSIONS

By means of two samples of projects of different types, we illustrated that takt planning methods vary due to consideration given to relative cycle times and associated resource costs of individual steps in their production processes, while accounting for the dependencies between those steps and between processes. The costs associated with the use of various throttles to change workload peaks play a role in the planning process. To our knowledge, little has been written to date about the relative costs of process steps in takt plans, and how these costs affect the opportunities planners have and choices they make when leveling workloads to determine the so-called “operable” takt time. We found that the CC method stemming from the ToC offers useful perspective on methods for takt planning especially in cases where a single, expensive resource or step clearly defines the process bottleneck, and the bottleneck’s cycle time well exceeds the cycle time of other process steps. More in-depth study is in order of how cost considerations affect the choice of a takt planning method.

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INTEGRATION AND DEVELOPMENT MODEL FOR SUPPLIER RELATIONSHIP MANAGEMENT IN CONSTRUCTION

Andreas Lepold[1], Marco Binninger[2], and Oliver Wolfbeiß[3]

ABSTRACT

The construction industry faces the challenge of selecting and developing partners for its projects. Although partner selection models and criteria have been extensively studied, the construction industry does not yet have optimized tools for selecting partners. Partner development is becoming increasingly important in the context of Lean Construction, which encompasses both Takt Planning and Takt Control (TPTC) and Last Planner System (LPS) approaches. To solve this challenge, a comprehensive literature review identified methods for partner selection in both the stationary and construction industries. The selection of the partners to be developed was presented using a best-practice example from the automotive industry. With the help of expert workshops, a model tailored to the selection of partners to be developed in the construction industry was developed and necessary criteria identified. The resulting conceptual model was tested through case studies and found to be effective. The selected criteria can be flexibly varied and adapted to the corporate strategy. The model was successfully applied to different partners of a general contractor with the help of case studies. The model is currently being tested in practice at a general contractor in an extended project scenario.

KEYWORDS

Supply chain management (SCM), Supplier relationship management, collaboration, trust, integration

INTRODUCTION

The application of lean management to construction was first introduced with the Egan Report Rethink Construction in 1998 (John Egan, 2014). The Lean approaches gained wider dissemination through the efforts of the International Group for Lean Construction and the successful implementation of the Last Planner System approach in 2000 (Ballard, 2000). However, the practical implementation of these approaches has been limited to project-based processing, which is characterized by a long start-up and run-down curve and no constant performing phase (Fagerlund et al., 2021). The focus has been on collaboration and cooperation both in practice and theory, and this project-based mindset is evident in approaches like the Last Planner System or Target Value Design, which are examples of lean construction implementation.

Newer approaches, such as Integrated Project Delivery (Bayazit et al., 2006) or Takt Planning based on the 3-level model (Dlouhy et al., 2016), take the concept a step further by

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viewing a project as a whole system. However, they are still primarily focused on single project execution, as this is the norm in the construction industry.

Continuous improvement is a crucial element of successful production systems, and cross-project learning is a key component of this process (J. M. Clark & K. E. Stecke, 1997). When projects are viewed as part of a larger system, they become interdependent and can be compared with one another. This approach can lead to advantages such as overlapping start-up and run-down phases, greater scaling effects, and a faster learning curve between projects. However, it can also lead to negative effects if approaches and problem-solving processes are not sustainable. The bullwhip effect, caused by a lack of stability, can have a significant impact on the overall system.

To address these challenges, new ways of thinking are necessary. In particular, the interaction between the implementation partners General Contractor (GC) and Subcontractor (SUB) must be considered more closely, as stability is largely generated by their collaboration. This interface between the micro and norm levels in the 3-level model (Dlouhy et al., 2016) is crucial to optimizing performance across projects. When both parties work together and share similar interests in the production system, the interface can be optimized to promote stability.

The construction industry can learn from other industries that have faced similar challenges in transitioning to production systems, and adopt the approach of systematic supplier relationship management (SRM) as part of supply chain management (SCM). This involves developing and integrating partners into the production system in a mutually beneficial manner, creating a win-win situation. While supplier selection methods are already applied in the construction industry (Cengiz et al., 2017), the SRM approach has yet to be widely adopted.

This paper applies the SRM approach, specifically the identification of developable partners, to the construction industry. The term "supplier" is used broadly in this context and includes subcontractors, craftsmen, planners, and all partners of a GC. Examples from the stationary industry are used as a basis for a model for the application of SRM in the construction industry. The research question addressed in this paper is: "How can the interaction between GC and other partners (Sub, craftsmen, planners, or suppliers) be developed sustainably on a micro level to positively influence stability?" By answering this question, the paper provides insights into how the construction industry can improve its production systems through the adoption of an SRM approach.

THEORY AND AS-IS SITUATION IN CONSTRUCTION

PRODUCTION SYSTEMS

The following chapter emphasizes the significance of partner management in a production system, drawing on the development of SRM in other industries and literature. Production systems refer to the comprehensive organization of production and comprise all the concepts, methods, and tools that contribute to the effectiveness and efficiency of the entire production process (Schuh & Stich, 2012). Contemporary production systems, such as the Toyota Production System, are founded on horizontal and vertical networking. Supply chain management, on the other hand, pertains to the management of the entire value chain (Wieland & Buchholz, 2011). The integration of external partners is particularly essential in the vertical value chain. For instance, Daimler and Bombardier have a vertical integration of up to 20% (Helmold & Terry, 2016). SCM can be segmented into customer relationship management, which defines the customer relationship from the GC's perspective, and supplier relationship management, which optimizes the relationship with the supplier (Wieland & Buchholz, 2011). Other industries have already recognized the following aspects related to SRM as they become a production system:

- Entering into and managing long-term relationships is becoming increasingly important in modern markets (Riemer, 2008)
- Relationship perspective instead of transaction-oriented views (Riemer, 2008)
- Traditionally the purchase range was regarded almost exclusively under cost aspects. The role of the procurement in the enterprise changes however and experiences increasing attention by the management (Stuart, 1997)
- A goal is thereby the structure of complex relationship networks with mutual information flows to a optimization of the entire creation of value chain (Riemer, 2008)

A key goal of SRM is to systematically evaluate and segment suppliers based on their current and future economic importance to the company (Dangelmaier et al., 2004). It is important to distinguish between partner relationships that primarily serve operational purposes and those that can help the company build strategic competitive advantages (Stuart, 1997). Figure 1 illustrates the evolution of SRM from a supplier as a procurer in the 1980s to a value creator in the present time. A clear example of this change can be seen in the automotive industry. In 2002, the car manufacturer, specifically the Original Equipment Manufacturer (OEM), produced 55% of the body of a car. Today, the industry average is 29% (Mercer Management Consulting & Fraunhofer-Institut, 2015). Similarly, BMW had a development depth of 70% in 1985, which decreased to 30% in 2007 (Richter & Hartig, 2007). At SMART in Hambach, suppliers contribute 75% of the product development and value creation (Wieland & Buchholz, 2011).

Figure 1: Evolution if the SRM (Helmold & Terry, 2016)

As a result, supplier management has become an integral function of transferring quality, cost, and delivery targets to the external value chain and synchronizing them with it (Helmold & Klumpp, 2011). The shift in value chain shares and consolidation has led to the concentration of competencies that were previously held by manufacturers with key suppliers, increasing the market power of these suppliers. Automotive manufacturers have responded to this trend with strategies such as "mega-supplier" or "key-supplier" approaches (Dölle, 2013). Additionally, early and systematic development of potential alternative suppliers is critical, as these suppliers can be integrated into cross-company processes through collaborative optimization (Helmold & Terry, 2016).

AS-IS SITUATION IN CONSTRUCTION

The construction industry is known for its project-specific execution and a highly fragmented and small-scale contractor market. In the German market, for instance, most contractors employ only a few individuals (Schul et al., 2007).

To secure subcontractors for a project, tendering and market comparison are usually the preferred methods, which can take up a considerable amount of time. While price is often the main criterion in the selection process, it is essential to consider other factors that may impact the total cost of ownership, such as rework, complaints, or failure (Helmold & Terry, 2016).

Project-specific processing has its own set of challenges. Companies collaborate for a limited time and then go their separate ways. During the initial stages of a project, friction can arise, which can either decrease or lead to a premature end of the partnership. Moreover, there is limited post-reflection or lessons learned, which does not promote the need for long-term and sustainable cooperation (Ferrada et al., 2016)

In practice, project-specific collaboration is governed by a contract that defines the technical and organizational framework conditions. The order is processed based on this contract, with the goal of achieving cost efficiency and minimizing interfaces. Most decisions are cost-driven, and there is a tendency to continue working together despite challenges due to time constraints.

As a result, large projects often experience budget overruns, delays, and a bad reputation, leading to legal proceedings and high insolvency figures (Ferrada et al., 2016; Narayanan et al., 2018).

METHOD

The procedure of the present article is based on two basic methods, namely literature research and expert workshops, which are discussed in more detail below.

In the first step of the literature research, the ideal process of partner development is presented based on the current standard literature. Based on this, the search for best practice examples will be conducted. The focus is on the automotive industry, which has been following the SRM approach for many years. The method of literature research was selected because it is a valuable tool for developing theoretical frameworks. The literature review was following the steps of selecting relevant sources, analysing, and synthesizing the information, and presenting the findings (Tranfield et al., 2003). Based on the partner development process and the preparation of the expert workshops, a comprehensive literature research identifies existing criteria for supplier selection. This research includes over ten relevant papers from 2009 to 2022. Based on the literature research, expert workshops are conducted in which the relevant criteria for partner development are identified and transferred to the construction industry.

Building on these criteria, further expert workshops will derive a model that can be used to identify the current maturity level of the partner as well as the need for development. The expert workshops will be conducted in collaboration with a GC. On the one hand, so that the developed model can be quickly transferred into practice, and on the other hand, to compare the criteria with the corporate strategy. The expert workshops as a method were chosen because it is an effective way of collecting knowledge (Bogner, 2005). Experts in our term are department leaders and specialists of a GC located in the German construction market. The experts were selected focusing on their role, market understanding, experience (over ten years average) as well as representing different perspectives e.g. project control, tendering, site management.

Subsequently, the capability of the model will be validated by means of six case studies to show the practical use of the model.

LITERATUR RESEARCH

IDEAL PROCESS OF PARTNER DEVELOPMENT AND BEST PRACTICE

In the chapter "Production Systems", it is evident that industries beyond the construction sector have reconsidered their approach to selecting partners. Furthermore, the manufacturing depths of companies in the stationary industry are approaching that of a general constructor. As such, this chapter presents a standardized supplier management procedure from the stationary industry, and emphasizes the successes achieved through the implementation of SRM. Figure 2 illustrates the supplier management process according to Hofbauer (2016), which comprises four sub-processes that are explained in greater detail below.

Figure 2: Supplier process (based on Hofbauer, 2016)

Supplier selection: At Audi AG, supplier selection serves to identify new and potential suppliers. The aim is to maintain and improve the supplier pool at the same level. The focus of supplier selection at Audi AG is on innovative and technology-driven suppliers. By collecting supplier information centrally, Audi AG achieves transparency throughout the company with regard to the market. Another advantage for Audi AG is the early identification of technological trends (Hofbauer, 2016).

Supplier evaluation and classification: As supplier evaluation (Wildemann, 2008) summarizes all processes, which serve for the production, selection and preparation as well as the evaluation of supplier information (Wildemann, 2008, p. 157). The aim is to verify that supplier performance meets defined requirements (Glantschnig, 1994). The supplier evaluation consists of the definition of the criteria as well as the quantitative and qualitative evaluation of the suppliers according to these criteria (Hofbauer, 2016). Audi AG conducts supplier evaluation not only at the time of award, but throughout the entire collaboration. The results of these evaluations are communicated to the supplier. Thus, a continuous improvement is achieved at the supplier. The classification of the suppliers serves to carry out a comparison with the corporate strategy and thus to identify the strategically relevant and irrelevant suppliers. The strategically significant suppliers are developed (Hofbauer, 2016).

Supplier development: Supplier development includes both the further development of existing suppliers and the qualification of new suppliers. It thus also supports supplier development. The aim is to increase the capabilities and performance of suppliers. This includes cooperation on a collaborative level as well as the transfer of know-how. At the same time, supplier development increases the competitiveness of suppliers among each other and thus reduces the dependency of the client. (Hofbauer, 2016). BMW and Porsche see supplier development as a core task. Development here extends to supplier academies and the secondment of experts. To develop its suppliers, Porsche also actively intervenes in the corporate policy of the partner (Helmold & Terry, 2016).

Supplier integration: Helmhold & Terry describe supplier integration as integrating the supplier into the existing product development process. Furthermore, it implies the use of the partner's know-how and the coordination of processes and systems. The aim is to minimize waste in the collaboration (Helmold & Terry, 2016).

EXISTING CRITERIA FOR SUPPLIER SELECTION

In the construction industry, supplier selection is a crucial activity, much like in other industries. However, the construction industry faces unique challenges due to three main factors: the type of collaboration, friction caused by a lack of development, and a lack of trust. The selection of suitable partners is thus critical for achieving economic success. (Bayazit et al., 2006; Zulficar et al., 2022)

Thanaraksakul and Phruksaphanrat (2009) examined 76 papers in a study for significant criteria for supplier selection and assigned a rank to each of the 33 criteria (Thanaraksakul & Phruksaphanrat, 2009). Helmold & Terry (2016) list ten criteria for supplier selection. In addition, Wieland & Buchholz, (2011) describes seven criteria for the type of cooperation between partners. Harshad et al., (2022) identified 21 criteria from the perspective of the lean, agile, green, and sustainable paradigms (Harshad et al., 2022). Kshaf et al., (2022) 19 factors that will improve the interaction between the subcontractor und the main contractor (Kshaf et al., 2022). Nath et al., (2021) identified ten project level enablers of collaboration (Nath 2021). Taherdoost & Brard (2019) identified 25 criteria in his study (Taherdoost & Brard, 2019).
In addition, Taherdoost & Brard make it clear that a company should only choose the criteria that are in line with the expectation of future suppliers (Taherdoost & Brard, 2019).

DERIVATION OF THE MODEL FOR PARTNER MANAGEMENT BASED ON EXPERT WORKSHOPS

The previous chapters demonstrated the effectiveness of an SRM model in other industries. In chapter "As-Is Situation in Construction the need for such a model for the construction industry was demonstrated. In this chapter, the methodology for building a partner model in the construction context is explained. The structure of the model is based on a maturity matrix. The rows represent the categories and the columns the degree of development.

THE CATEGORIES OF THE MODEL

Table 1: Example derivation of the subcategories for the partner model (Expert workshop, Nov. 14, 2022)

Attributes from supplier selection	Influence of the attribute on a service to be provided, a product or an activity (in the construction context)	Derived subcategory
Quality, Delivery, Performance. Reliability	Influences the control effort of the partner	Focus on the control

Table 2: Overview of the ten derived categories for the partner model and the respective definition (Expert workshop, Nov. 14, 2022)

Attributes from the supplier selection	Sources	Subcategory of the model	Definition
Quality, Delivery, Performance, Reliability	(Becker, 2014); (Thanaraksakul & Phruksaphanrat, 2009); (Helmold & Terry, 2016); (Taherdoost & Brard, 2019); (Nath et al., 2021)	Focus of the control	Degree of control effort of the partner based on quality and on-time delivery
Mutual trust and easy communication	(Taherdoost & Brard, 2019); (Nath et al., 2021)	Know-How Transfer	Degree with which knowledge is shared between the parties
Warranties and claim policies	(Thanaraksakul & Phruksaphanrat, 2009); (Taherdoost & Brard, 2019)	Contract type	Degree of mutual dependence
Desire for Business, Management and Organization	(Becker, 2014) (Thanaraksakul & Phruksaphanrat, 2009)	Time commitment	Duration of cooperation
Professionalism, Attitude and strategic fit, Communication system	(Taherdoost & Brard, 2019) (Helmold & Terry, 2016), (Nath et al., 2021)	Level of cooperation	Degree of efficiency of cooperation
Flexibility and Reciprocal arrangement	(Taherdoost & Brard, 2019) (Becker, 2014) (Thanaraksakul & Phruksaphanrat, 2009)	Scope of service	Degree of the partner's own product development
Innovation and R&D, Personal trainings and development, willingness of innovation	(Taherdoost & Brard, 2019) (Thanaraksakul & Phruksaphanrat, 2009) (Helmold & Terry, 2016)	Optimization and development	Degree of partnership business development
Production, facility and capacity, technology aspects	(Taherdoost & Brard, 2019) (Thanaraksakul & Phruksaphanrat, 2009) (Helmold & Terry, 2016)	Standardization	Degree and scope of standardization
Financial status, cost management and transparency, financial strength of the supplier including payment modalities	(Taherdoost & Brard, 2019) (Thanaraksakul & Phruksaphanrat, 2009) (Becker, 2014)	Willingness to invest	Monetary importance of a decision for the partner
Other criteria	(Hofbauer, 2016)	Strategic relevance	Strategic importance of the partnership

In chapter "Existing criteria for supplier selection" more than ten relevant papers and over 80 criteria were identified. The following model is intended to solve the construction-specific problems of the partner selection. Additionally, the model is intended to be applicable to all partners and not limited to suppliers of physical products. Therefore, the criteria are used as bases for the categories of the following model and specifically adapted. To adapt the categories to the construction sector, the influence of each attribute in the construction context on a service, product, or activity to be performed was investigated. Table shows an example of this adaptation. In addition Table 1 shows which of the supplier selection attributes serve as the basis for the subcategories. The definition of the 10 derived subcategories can also be taken from (Expert workshop, Nov. 14, 2022).

THE FOUR STAGES OF DEVELOPMENT OF THE MODEL

From a broader perspective, there are two stages of development within the system: "in" and "on" the system. "In" the system refers to partners who are functioning within the production system, but who do not have a strong interest in further developing it. These partners can be elevated to the next level through targeted development efforts. The more advanced stage is "on" the system, where partners with a higher level of development can be identified and have a vested interest in contributing to the production system.

To provide more detail, the system can be divided into four levels. Level 0 is the starting point, which all partners must reach. Levels 1 and 2 can be achieved independently, but Level 2 requires that all criteria be met in order to gain a holistic understanding of the system. This approach helps to prevent a single criterion from disproportionately influencing the allocation of resources. Level 3 represents an ideal situation, but no partner has yet reached this level in practice (see Figure). It represents the aspiration for a perfect partner.

In summary, the system has two stages of development: "in" and "on" the system, and is divided into four levels, with each partner starting at Level 0 and aiming to progress to Level 3. (Expert workshop, Nov, 14, 2022)

THE MODEL

In order to classify partners and identify their development potential, each level is defined in relation to the respective category. With ten categories and four levels, a 10x4 matrix is created. Level 0 represents the minimum requirement in the corporate context, while level 3 represents an idealized, maximum possible state. The definitions for levels 0 and 3 serve as the framework for the definition of intermediate levels 1 and 2. These definitions are chosen in such a way that from level 2 onwards, the categories are correlated with each other. The goal is to ensure that partners are selected holistically and developed across multiple categories, rather than only within a single category. Figure 4 shows the model with the development stages and the ten defined categories. (Expert workshop, Nov. 21, 2022)

For the further development of partners, two categories play a special role: investment will and strategic importance. If a partner reaches a defined threshold in these categories, the company will have the will to develop the partner. The action portfolio based on strategic importance and investment will is shown in Figure . (Expert workshop, Nov. 21, 2022)

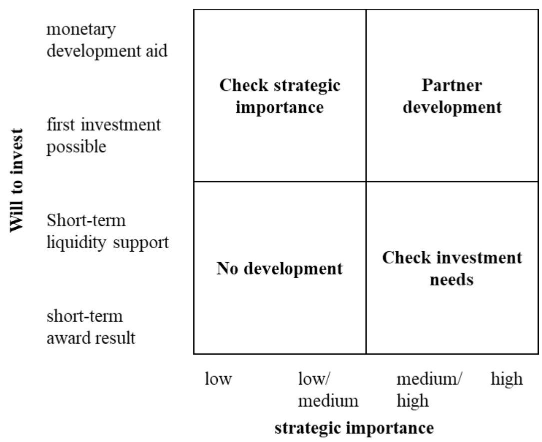

Figure 3: Recommendations for action on partner development based on strategic importance and willingness to invest (Expert workshop, Nov. 14, 2022)

CASE STUDIES

In the following, the applicability of the model for the classification of partners as well as for the development of the same is examined. As part of the expert group, six scenarios for the classification of partners and six scenarios for the development of the partners were examined. Two case studies for Classification of Partners and one case study for Development of the Partners are explained below as examples. (Expert workshop, Nov. 21, 2022)

APPLICATION OPTION 1: CLASSIFICATION OF PARTNERS

Due to the clever choice of categories, the model can be applied universally for partnerships. From the classic SUB to the material supplier and to the planning partner. This is illustrated below in two examples for the respective level (see Figure).

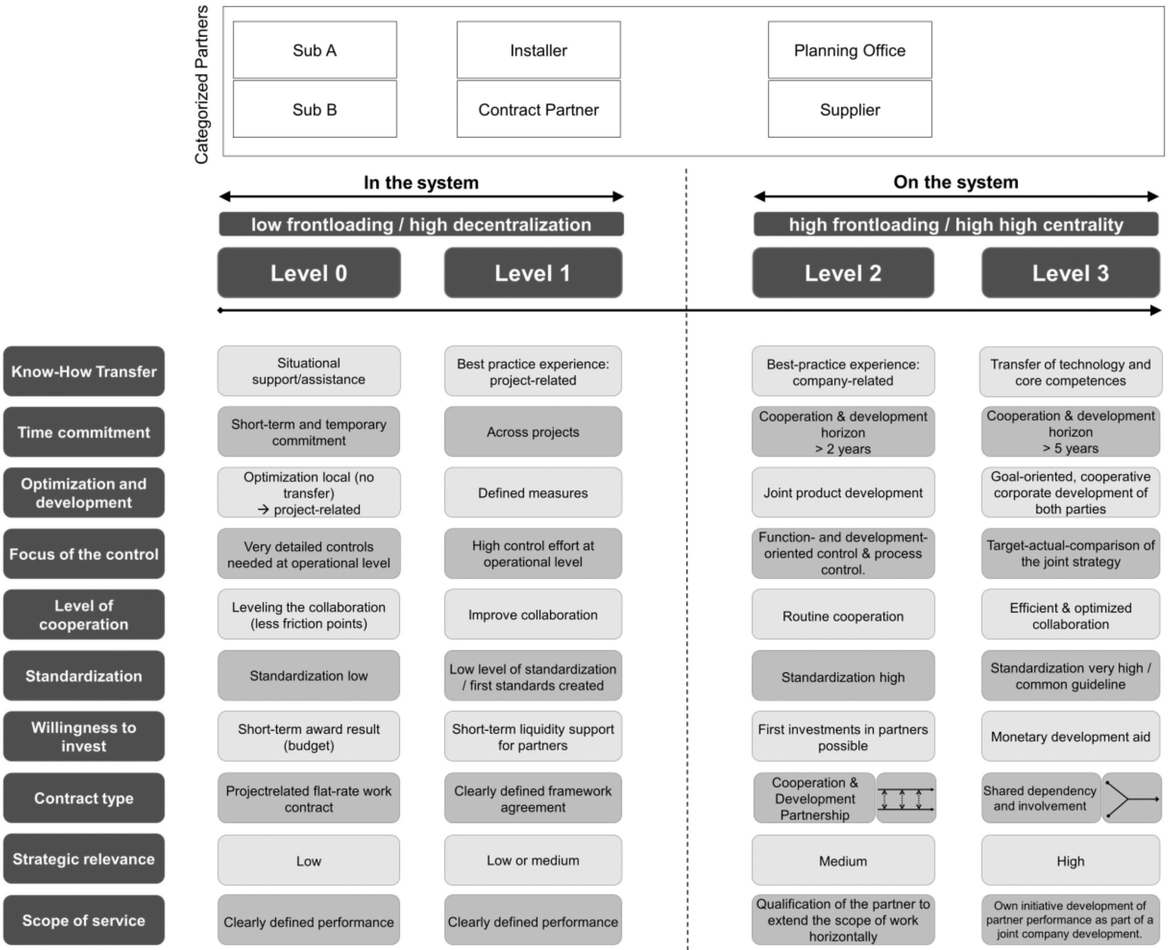

Figure 4: Partner selection, integration and development model (Expert workshop, Nov. 21, 2022)

Example Stage 0, Subcontractor A and B:

A su at Level 0 requires close quality control, as well as monitoring of quantity, adherence to schedules, and location. Know-how is transferred unilaterally, with the GC providing information to the subcontractor. Due to the nature of the contract, which is typically a project-related lump sum contract, the cooperation is limited in time. The collaboration is based on aligning the respective tasks, which is possible because the scope of the service is clearly defined and the contractor is not expected to develop the product independently. As a result, the subcontractor may optimize their work but without considering subsequent trades. The contractor's approach may not be highly standardized, and their relevance to the company's success is typically low, allowing the focus to be on the award result. (Expert workshop, Nov. 21, 2022)

Example Stage 2, Planning Office and Supplier:

Only partners who demonstrate a willingness to work on the system are placed in Stage 2. These partners have proven or can demonstrate that operational level control is unnecessary, and thus the focus of control shifts to development and process levels. Know-how transfer is not limited to individual processes or projects but encompasses all affected areas. The cooperation between the two partners is formalized by entering into a cooperation and development partnership with a commitment of over two years. Due to the long-term commitment, the cooperation is focused on routine and efficiency. The development partnership makes it possible to support the partner in horizontally expanding their scope of tasks, with a joint development of the product towards a high level of standardization (both physical and digital products). Achieving these objectives may require an initial investment in the partner (e.g. expanding the service infrastructure at the partner), which can only be justified by a medium strategic relevance of the partner. (Expert workshop, Nov. 21, 2022)

APPLICATION OPTION 2: DEVELOPMENT OF THE PARTNERS

Based on the practical examples, it is shown how a partner can be developed.

Scenario 1 Partner needs to be developed, Subcontractor A from level 0 to level 1:

Changes in environmental conditions can lead to the need for partner development. For example, if a supply deficit increases the strategic relevance of a subcontractor from low to medium, it becomes necessary to develop this subcontractor into a framework contract partner and bind them across projects to minimize production risks (Figure). To successfully develop the partner, it is important to improve the cooperation with them, creating a basis of trust for project-related exchange of know-how. At the beginning of the partnership on level 1, a very detailed control is still necessary, and the optimization or development takes place within a narrow framework, requiring short-term liquidity support. (Expert workshop, Nov. 21, 2022)

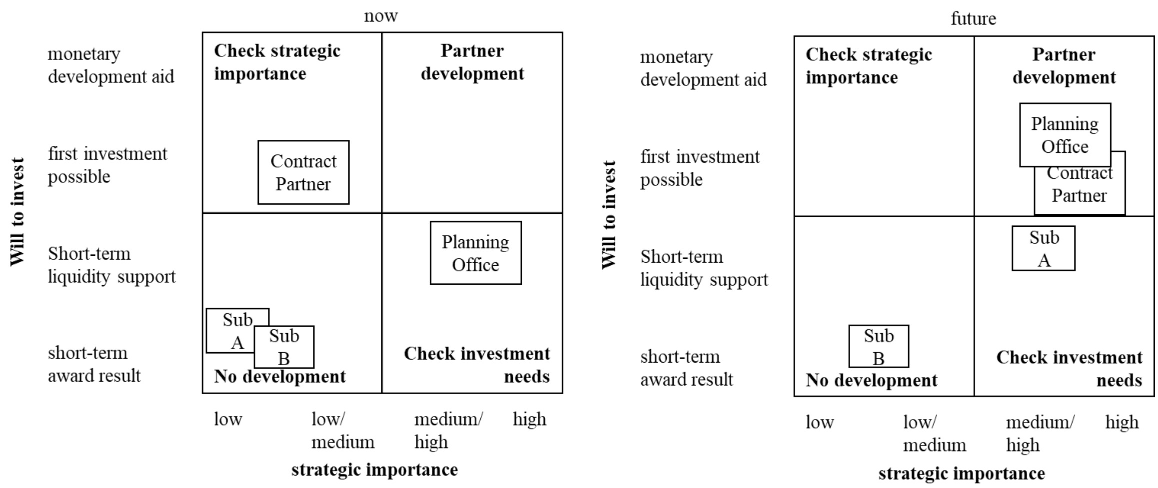

Figure 5: Example scenarios for the classification of partners in the event of a change in strategic importance and the willingness to invest (Expert workshop, Nov. 21, 2022)

CONCLUSION

Many industries have transitioned from a purely cost-driven approach to a holistic approach when selecting partners. The construction industry needs to follow this trend. The article compares the automotive industry to the construction industry, where project-specific execution, a fragmented and small-scale contractor market, and a focus on cost-efficiency and short-term partnerships have hindered the development of effective SRM. To boost production efficiency and effectiveness in the construction market, a viable solution may involve shifting its focus towards forging long-term, sustainable relationships with suppliers and partners. The paper presents a model for classifying existing and potential partners. Practical scenarios from a GC show that development stages can bring transparency for both clients and partners. The model shifts procurement from a best-price approach to a sustainable development approach for partners. Parties can use the model to decide whether and how they can deepen the partnership. Additionally, the model supports management in categorizing partners by maturity level. By creating a long-term development perspective, partners are bound to each other, promoting common understanding of goals, joint learning, and sustainable interaction. It is theoretically proven within the case studies, that the research question can be confirmed. The developed model is the base for the interaction between the GC and other partners and has the focus on developing a sustainable and stabile partnership between the parties.

This concept paper was developed in collaboration with a GC, and the model is currently being tested in practice.

DISCUSSION AND OUTLOOK

To answer the research question "How can the interaction between GC and other partners (Sub, craftsmen, planners, or suppliers) be developed sustainably on a micro level to positively influence stability" a model for partner selection has been successfully developed and tested in the case studies. The model enables the GC to choose the project partner in the right way and even develop him in a long term. Also the model proves to be a fast and efficient method to create an overview of the current partners. The case studies have shown that the model can be applied to suppliers of physical products as well as to subcontractors, planning offices and other partners of a GC for effective supplier management and thus supports the critical phase of partner selection (Bayazit et al., 2006; Zulficar et al., 2022). In accordance with the best practices from the automotive industry (Hofbauer, 2016), the clear criteria and the classification of the partners create transparency about the current development status of both parties. The model makes it possible to identify a partner's development potential in advance and to continuously track and control its development. By promoting transparency and recognizing development potential, the stability of the partnership can be positively influenced. Although the model has been successfully tested in the case studies, its effectiveness has yet to be tested in practice. In this work, the criteria were chosen according to the strategy of the general contractor (Taherdoost & Brard, 2019). It is therefore necessary to examine how the selected criteria fit the entire construction industry.

The model is currently in an initial testing phase and has yet to be extensively tested in practice. It is necessary to verify its applicability during the practical phase, which precludes final evaluations currently. Additionally, the practical phase will determine whether the selected categories require supplementation or adaptation. In further investigations, the model's impact on the entire construction industry should be examined, possibly through surveys of partners.

To select the best option from multiple alternatives, a metric should be developed and a threshold defined. As the model includes both quantitative and qualitative criteria, it would be useful to investigate the effectiveness of decision models from multi-criteria-decision-making (MCDM) such as the Analytic Hierarchy Process (AHP) (Thomas Saaty, 1980) or the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Wang et al., 2009).

To define and track partner development, the experiences from the stationary industry suggest creating a catalog with measures for partner development up to the partner academy. Through a portal access, partners can monitor their current evaluation and goals required for further development. This approach will enhance transparency, interaction, and communication among stakeholders.

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UTILISING DESIGN THINKING TO REFINE CUSTOMER REQUIREMENTS – A CASE STUDY USING THE CONCRETE SUPPLY CHAIN AS AN EXAMPLE

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ABSTRACT

The concrete supply and value chain in Germany is characterised by a large number of project participants and, as a result, numerous interfaces must be regulated continuously in every building project. The industry's high degree of fragmentation leads to a situation where information must be prepared and transferred from one system to another with a great deal of manual effort. However, initial attempts to establish a continuous information chain using digital technologies did not bring the desired success. It became clear that the past attempts placed an excessive emphasis on technological aspects and neglected the needs of the actual users. This paper describes a human-centred research methodology that puts the human being and therefore the ultimate customer more in the foreground and actively involves the person in the development of solution concepts. The aim is to reduce waste as well as repetitive and unnecessary activities for those involved in the concrete supply chain. For this purpose, the Design Thinking method is used and adapted to the current context. Summarized this paper contributes an exemplary procedure on how to use Design Thinking to refine customer requirements using the concrete supply chain as an example.

KEYWORDS

Collaboration, customisation, logistics, Design Thinking, concrete supply chain.

INTRODUCTION

The German construction industry is highly fragmented. According to the Federal Statistical Office (2020), 99.9 % of the companies in this country have fewer than 250 employees and 90 % of the companies have fewer than ten employees. In addition, the German construction industry is characterised by a high degree of complexity, which is increased, among other things, by a large number of project participants from different disciplines. This constellation leads to a heterogeneous use of software and hardware and thus to insufficiently interlinked knowledge silos, with many media and information breaks. (Shen et al., 2010)

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This paper deals with a specific area within the German construction industry, namely the concrete supply and value chain. Like the construction industry, this sub-sector is also highly fragmented. According to the annual report of the Federal Association of the German Ready-Mixed Concrete Industry (BTB, 2020b) the German ready-mixed concrete industry consists of 535 companies with 10,590 employees and a total of 1,880 ready-mixed concrete plants.

This situation is particularly problematic for the flow of information between the process participants. In the supply and value chain of concrete, information must be collected at different process steps and permanently documented (cf. DIN EN 206 , DIN 1045-2). This process is currently carried out manually and need to be connected and documented afterwards in a complex manner. For example, the delivery of concrete from the mixing plant and its arrival at the construction site must be documented. The risk of information errors due to the "human factor" is particularly high here (Lanko et al., 2018). At the same time, the communication channels in the supply chain of building products are often limited to conventional telephone calls, emails or faxes (Li et al., 2015). This circumstance makes an automatic exchange of information and easy traceability very difficult.

Various organisations have already attempted to develop a solution to this problem in the past (BTB, 2020a; edr software GmbH, 2019). However, the systems developed were only used in closed ecosystems limited to a few project participants. A large-scale application failed not because of a faulty system, but because of the acceptance of the users. A closer look at the systems reveals that the focus in the development of the solutions was on the technology and not on the customer. In a round of interviews with experts from the concrete industry, the system failure was identified as the result of incomplete collection of user/customer requirements and its lack of incorporation into the solution design (SDaC, 2022).

The aim of this paper is to examines the problem more closely and focusses on the customer requirements with the help of a human-centred research approach. For this purpose, a human-centred research method was selected and used, adapted, and extended to the present situation.

In the further course of the paper, the literature review to human-centric Design is presented. Afterwards the basics of the Design Thinking method are first discussed, before the actual procedure is presented. This section forms the main part of the paper. The individual steps in the process are explained in detail and examples of interim results are given. Finally, an outlook and a critical appraisal of the results are provided.

LITERATURE REVIEW

System development used to be based on predefined process steps that did not involve the user much, if at all. In the 1980s, the cost of computer hardware dropped significantly, giving many people access to computers. The problem, however, was that computers were difficult to operate. Therefore, with the involvement of users, new systems were developed that were simple and easy for everyone to use. This laid the foundation for the involvement of users in the development of systems and products.(Cockton et al., 2016)

User-centered design puts the user and their relationship to technology at the forefront of an application's development process (Zhang et al., 2020). Understanding the characteristics and needs of people leads to technologies that create added value for them. Additionally, understanding the customer results in a more usable product, financial savings by avoiding bad investments, and safer systems. A method to achieve an understanding of the user is, for example, to ask the following questions of Ritter et al. (2014).

- What do people do? Methods for gaining knowledge from data are used for this purpose.
- Why do people do what they do? Insights are gained into people's unconscious and conscious motivations.
- When are people likely to do something? Patterns of human behavior are identified.

- How do people decide to do things the way they do? An understanding is built up about people's possibilities for action, limitations, and resources.

While user-centered design examines the interaction of the user with a system, human-centered design focuses more on the abilities and characteristics of the people who are influenced by the system. The human being is considered the central element of the system (Spitler & Talbot, 2017). Nowadays, more and more systems are being created in which humans no longer interact with technology only as users but in a mixed human-machine interaction. Nevertheless, this can be influenced by new technologies. This makes it necessary to consider humans and their effects on development. Human-centered design takes into account both immediate and long-term points of contact between the human and the system. (Ritter et al., 2014)

To create user-centric design, there are several methods and approaches that designers can use. Personas are fictional representations of users based on research that help guide design decisions by providing a clear understanding of users' needs and goals (KSRI, 2020). User journey mapping is another method that involves visualizing the steps a user takes to accomplish a task, which can identify pain points and opportunities for improvement (Lewrick, 2018). Wireframing is another technique where low-fidelity visual representations of a user interface are created to explore different design options (KSRI, 2020). Prototyping is a critical step in the design process, where high-fidelity mockups of a product or service are created to test with users and refine the design (Uebernickel et al., 2015). Usability testing is another essential step to evaluating the usability of a product or service by testing it with representative users (KSRI, 2020). Co-creation is an approach that involves engaging users and other stakeholders in the design process to ensure their needs and ideas are incorporated (Schallmo & Lang, 2020). Design thinking is a problem-solving approach that emphasizes empathizing with users, defining the problem, ideating potential solutions, prototyping, and testing (Schallmo & Lang, 2020; Uebernickel et al., 2015). This approach ensures that the design is centered around user needs and goals. Agile development is a methodology that emphasizes collaboration, flexibility, and continuous improvement (Lewrick, 2018). This allows designers to iterate on the design based on feedback and new information, leading to a more user-centric design. Overall, these methods and approaches help designers create solutions that are centered around the needs of the users (Uebernickel et al., 2015).

For this study, the design thinking method was chosen to investigate the problem described in the introduction. Among other methodologies, design thinking is very customer-centered and has already been successfully applied in the past in various studies in the construction industry (Spitler & Talbot, 2017; Zhang et al., 2020). In addition, other methods, such as developing personas and forming hypotheses, can be included in the process. In the next chapter, the methodology is presented and the essential features are discussed.

METHOD

Design Thinking is used to create customer-oriented products, services, and processes, and to align them in the most customer-centric way feasible (Schallmo & Lang, 2020). Instead of developing solutions for which suitable areas of application still need to be found, Design Thinking offers a method for examining the problems and developing human-centred solutions. According to Erbeldinger et al. (2015) Design Thinking focuses on inventive thinking with a radical customer or user orientation. The methodology requires several iterations that serve to successively gather user feedback and consequently generate new knowledge and develop more appropriate solutions (Schallmo & Lang, 2020). In addition, an interdisciplinary team is used, which deals intensively with the issue over a period of time (Plattner et al.; Schallmo & Lang, 2020).

In the context of this work, the Design Thinking Microcycle according to Uebernickel et al. (2015) was chosen and combined with the procedure according to Schallmo and Lang (2020). The Design Thinking Microcycle consists of the following five steps (Figure 1):

1. **Step 1: Problem definition**
   Initially, it is important to look at and examine the problem as neutrally as possible and with a broad field of vision. In particular, a common understanding and a common perspective should be created within the team working on the problem. In this phase, it is important to deal intensively with the user and to understand the needs. This can be achieved through a lot of personal contact in the form of discussions or workshops. It is also very helpful to take on the role of the user for a few days and, for example, to carry out the work yourself. This approach gradually increases the knowledge about the user and his problems.
2. **Step 2: Need finding**
   The relevant conclusions are then collected, analysed, and interpreted. This procedure makes it possible to develop a user profile that demonstrates characteristics, needs and problems.
3. **Step 3: Ideating**
   The next step is to gather possible ideas for solutions based on the knowledge already collected. The ideas aim to fulfil the identified needs of the user. Relevant ideas are identified through a selection process.
4. **Step 4: Prototyping**
   Afterwards the collected ideas need to be transformed into testable prototypes as quickly as possible. The level of detail of the prototypes increases with each iteration loop. The aim is to identify the best properties of the prototypes quickly and without much development effort, and to improve them continuously in the following iteration loops.
5. **Step 5: Testing**
   In a test phase, the prototype is presented to its future users and checked for practicality. Prototypes that are not suitable are already dropped in early iteration loops. This allows the development team to concentrate on particularly promising prototypes or functions.

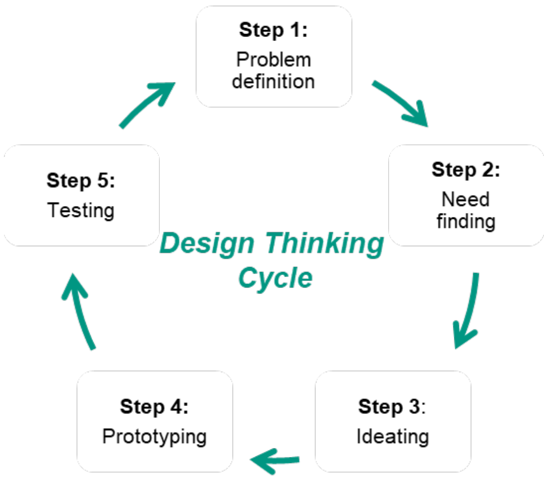

Figure 1: Design Thinking Microcycle according to Uebernickel et al. (2015)

As already mentioned, the Design Thinking Microcycle takes place in several iterations. Once an iteration has been completed, the cycle starts again from the beginning by revising the problem definition and adapting it based on the findings. This procedure makes it possible to quickly produce presentable results and to further concretise them after each iteration loop. In the next chapter, the Design Thinking Microcycle is applied to the concrete supply chain. The actual procedure and the methods used are described. In addition, exemplary results are shown.

RESULT

PROBLEM INVESTIGATION (STEP 1-2)

The case study started with arranging ***a panel of* experts**. As part of the Smart Design and Construction (SDaC) research project and in cooperation with the German Concrete and Construction Technology Association (in German: Deutschen Beton- und Bautechnik-Verein E.V. - DBV) and the Community for supervision in construction (in German: Gemeinschaft für Überwachung im Bauwesen E.V. - GÜB), a working group was initiated. The SDaC project is a research project funded by the Federal Ministry of Economics and Climate Protection of the Federal Republic of Germany, with the aim of developing a platform for Artificial Intelligence (AI) applications in the construction industry. The interdisciplinary consortium with numerous partners is led by the Institute for Technology and Management in Construction at the Karlsruhe Institute of Technology (KIT). DBV and GÜB are domain experts and active in the field of concrete construction for several decades. The expert panel is in turn composed of representatives of the concrete value and supply chain and most recently consisted of 28 people from 20 different organisations. The expert panel forms the group of people in which ideas and approaches were later presented and discussed. For this purpose, the current state of development was presented to this group at short intervals. The form and methods used will be explained further below.

To learn more about the participants in the supply and value chain, ***personas*** representative of each user group were developed. The identified relevant user groups are: concrete distributor, concrete mixer driver, shell construction manager and quality supervisor. Creating a persona is a method used to represent a fictitious user as authentically and realistically as possible. The persona represents a member of a real focus group. In the representation of the persona, individual characteristics, wishes and tasks of a user are considered. For example, it represents the age, gender, possible family relationships, personality, desires (“gains”) and frustration (“pains”) as well as tasks ("job-to-be-done"). The information on the persona is based on conclusions drawn from recordings, experiences and our subjective perception and thus represents how the user would behave from our point of view. (Lewrick, 2018) A persona from the concrete supply and value chain is, for example, the shell construction site manager. The persona of the shell construction foreman developed in the case study is shown in Figure 2.

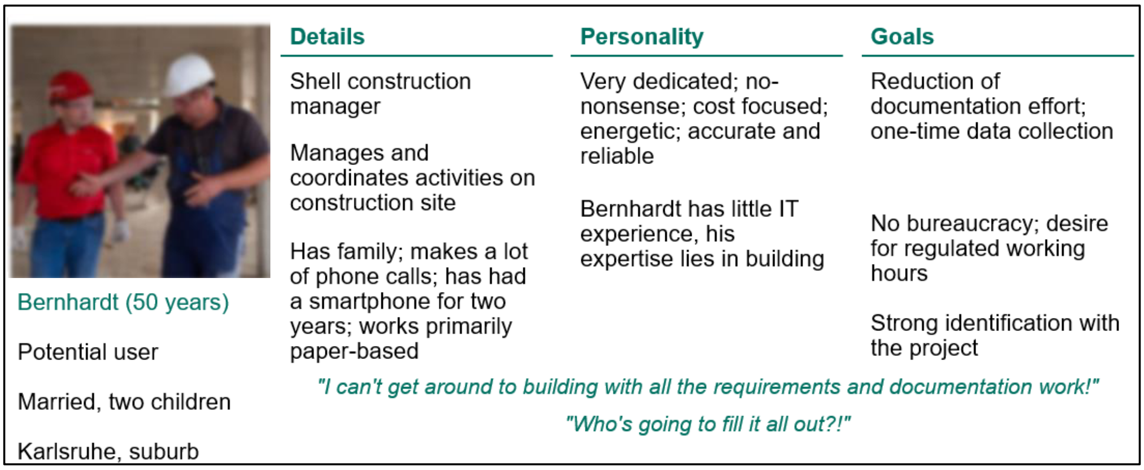

Figure 2: Persona shell construction manager

The developed personas were regularly reviewed and adapted within the Design Thinking cycle. For this purpose, expert interviews and on-site observations were used. This procedure successively sharpens the image of the potential users with each iteration loop and thus leads to regular insights into the behaviour of the users.

In addition to the personas, hypotheses were formed to add information. The hypotheses serve to make the knowledge gained tangible. The development and verification of hypotheses is oriented towards the three steps according to Kornmeier (2018). The three steps can be iteratively repeated as often as desired according to the Design Thinking cycle.

1. A hypothesis is formed about a causal relationship that requires explanation. The hypotheses describe a problem or a situation but can also represent a proposed solution at the same time. In relation to the shell construction manager, for example, a hypothesis is: "The site manager does not have enough time to carry out careful documentation. A simple, quick process is necessary".
2. The hypothesis is tested against reality through conversations or observations and falsified if necessary.
3. This process of constantly forming and testing hypotheses is repeated regularly until statements are found that best represent reality.

Figure 3 shows examples of hypotheses for the persona of the site manager. In addition to the actual hypothesis, the figure also describes how the hypothesis can be tested.

Hypothesis	Assumption	Measurement
Hypothesis 1	The construction manager does not have enough time to carry out careful documentation: A simple, fast process is needed.	Required time, number of errors
Hypothesis 2	The user has little prior knowledge of the requirements for the delivery. This results in insufficient / incorrect testing.	Years of professional experience of the tester, number of errors
Hypothesis 3	The matching of delivery bill to order form is insufficient. A daily updated and supporting digitalisation would be ideal.	degree of documentation, interviewing persons concerned
Hypothesis 4	External data (e.g., weather data) are not considered during the ordering process: Integration can optimize or facilitate ordering and documentation.	Data reconciliation
Hypothesis 4	Documents for documentation (individual documents) are not linked to each other: The same information must be entered in several places.	Number of multiple accesses to information, single documents with the same information

Figure 3: Hypotheses on the persona of the shell construction manager

The development of personas and hypothesis has created a sharper picture of the actual clients of a later solution. In particular, the problems and difficulties of each group of people have been addressed. One conclusion from this process was, for example, that the site manager is not averse to using digital technologies in principle, but that he hardly has time to deal with them during his working day. The development team was not previously aware of this connection in this much detail, and it was only highlighted through the development and validation of the personas.

SOLUTION DEVELOPMENT (STEP 3-5)

With a deeper understanding of the customer requirements (compare step 1-2), it is now possible ***to develop ideas and suitable solutions (step 3)***. One idea that quickly emerged from the intensive examination of the problem situation is the two-step approach. The two-step approach is particularly interesting because it quickly improves the current situation. The quick improvement of the current situation was one of the customer requirements identified earlier.

The two-step procedure is illustrated in Figure 4. The first stage is using an Artificial Intelligence-based scan function to extract machine-readable data from the delivery notes as quickly as possible and therefore at short notice, to circumvent the digital-analogue media breaks. The necessity for this first stage is the high fragmentation of the concrete supply and value chain. The high number of different companies makes a direct standardisation of a digital exchange format extremely time-consuming due to the necessary agreements. The Design Thinking Microcycle in connection with the presentations of personas and hypothesis have confirmed this fact. For this reason, the development of a digital interface is not planned in the long term until stage 2.

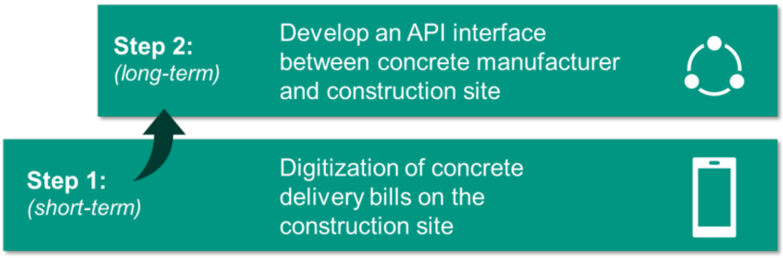

Figure 4: Graduated implementation model for a continuous information chain

After a suitable idea was identified, the team started with ***prototyping (step 4).*** The aim was to design a technical concept for each stage as quickly as possible for the software development later. To this end, conceivable technical approaches were quickly converted into testable prototypes using ***Mock-Ups.*** A Mock-Up gives the user an overall impression of the planned system without necessarily actually functioning (Lewrick, 2018). The future customer of the software application is placed at the centre of the development. Mock-Ups are ideal for expert interviews to convey ideas and approaches to the interviewer, visually and in a way that is easy to understand. For the presentation of the Mock-Ups, three levels of presentation were chosen: low, medium and high resolution (KSRI, 2020). Each level was ***tested through several iterations (step 5)*** in user interviews. The difference between the individual stages is the increasing level of detail of the prototype. By doing so the interviewer automatically focuses on the feedback of the viewer. Too specific content or a high-quality design can distract the viewer and therefore influence the feedback. For example, in an early phase of the Mock-Up development, it is not necessary to gather feedback about design aspects such as the button size or the colour scheme, but rather on the actual functionalities. The three levels are exemplarily shown in Figure 5.

Figure 5: Three levels of Mock-Ups according to KSRI (2020)

1. ***Low Resolution:*** This level shows the ultimate user flow in the application. Individual pages in black and white represent the necessary steps that a user must go through to achieve the desired result. The user flow thereby determines the number of pages and the click sequence in the later software.
2. ***Medium Resolution:*** At this stage, the first basic elements within the pages are defined and mapped. The resulting wireframes are already clickable but still in black and white. The focus of the feedback at this stage is on the completeness of the required functions. The design and layout do not play a role at this stage.
3. ***High Resolution:*** This third level already shows all details of the later application. This impression is created by a graphically appealing design with a high level of detail. The viewer may not be able to tell the difference between the Mock-Up and the final application.

After finishing the third level of the Mock-Up development, the final software development had to be carried out and the Artificial Intelligence-based scanning software and the API interface had to be created. The respective Mock-Ups provide a clickable prototype for this, which only needs to be technically replicated. Due to the short-cycle and the human-centred Design Thinking approach, the ***agile software development method is*** used for the development. Unlike, for example, the waterfall model or the Rational Unified Process (RUP), which tend to be considered less effective, heavyweight and unable to deal with short-term changes. The goals set were readjusted or completely redefined in each sprint by means of evaluated feedback (Martin, 2020). The four guiding principles and the twelve principles from the Agile Manifesto were used for orientation (Beedle et al., 2001) which according to Bergsmann (2018) form the cornerstones of practically all agile approaches.

DISCUSSION

The primary goal of any business is to satisfy its customers by providing products and services that meet their needs and requirements. However, determining what customers want and need is not always a straightforward process. Customer requirements can be complex and multifaceted, and understanding them requires a structured approach. In recent years, Design Thinking has emerged as a popular approach for solving complex problems, including those related to customer requirements. This paper discusses the use of design thinking to refine customer requirements, using a case study of the concrete supply chain as an example.

The concrete supply chain is a complex and multifaceted system that involves many stakeholders, including contractors, suppliers, and customers. To better understand the customer requirements in this supply chain, a Design Thinking approach was used. The process involved several steps, including the development of personas, hypothesis, and mock-ups. Design Thinking is a human-centered approach to problem-solving that highlights empathy, experimentation, and iteration. At its core, Design Thinking is about understanding the needs and wants of users and using that understanding to create innovative solutions that meet their needs. When it comes to customer requirements, Design Thinking can be a valuable tool for businesses. By using Design Thinking, businesses can gain a deeper understanding of their customers' needs and use that understanding to develop products and services that better meet those needs.

The Design Thinking process used in the case study resulted in several insights and improvements for the concrete supply chain. For example, the process revealed that customers in the supply chain were concerned about the quality of the concrete they received and the reliability of the delivery process. As a result, the developed system was reorganized to improve quality control and delivery scheduling. Additionally, new services were added to the process to help customers track their orders and communicate with suppliers.

The implications of these findings extend beyond the concrete supply chain. By using Design Thinking to refine customer requirements, businesses can gain a deeper understanding of their customers' needs and develop more effective solutions to meet those needs. This can lead to increased customer satisfaction, improved products and services, and ultimately, a more successful business.

CONCLUSION

The supply and value chains examined in this case study demonstrate significant possibilities for digitalisation. The application of the Design Thinking method within the framework of the research methodology proved to be very beneficial. Particularly during the phase of the problem investigation, the approach enabled an in-depth examination of the problem. Instead of focusing directly on a solution and working it out with the participants, a significant amount of time was spent in an early phase, analysing the problem in depth. Leading by this procedure, a two-stage solution implementation approach was formed. The use of Mock-Ups in the phase of the solution development also proved to be very helpful. The visualisations increased user understanding by giving the user a general understanding of the solution that have been presented. In comparison, it would have been much more difficult to present concepts to the future user only through explanations, text documents or similar. The three stages of Mock-Up development ensured that the focus of the feedback was targeted.

This article provides, for the first time, a customer-centric approach to analyse system requirements. The requirements obtained in this way can then be transferred into a type of requirements specification. Due to the fixed implementation time, only a limited number of methods could be tested and applied. Within the framework of the Design Thinking approach, however, there are many other methods (cf. job-to-be-done, stakeholder map, data canvas or similar) that can be integrated into the procedure as desired. For future work, it is recommended to also test these methods. Furthermore, the procedure presented in this paper has so far only been applied in the supply and value chain of concrete. For this reason, this case study doesn't create a representative sample size and should be applied to other disciplines and industries.

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A FRAMEWORK FOR OPTIMIZING MATERIAL MANAGEMENT PROCESSES IN OIL AND GAS EPC PROJECTS

Mahmoud Daghlas[1], Rachad Bou Nasser Eddine[2], Michel Tabet[3], and Mayssa Kalach[4]

ABSTRACT

In the specialized engineering, procurement, and construction (EPC) oil and gas industry, the monetary value of procurement equates to more than engineering and construction combined. However, material management processes are yet to evolve from conventional push systems to more efficient ones. The application of lean concepts to eliminate the waste embedded in the material flow processes of construction projects has become a proven practice for reducing cost overruns and schedule delays. To this end, the objective of this study is to develop a framework relying on just-in-time delivery and pull systems to enhance material management processes in EPC projects. Namely, the proposed framework introduces changes to the responsibility matrix and sets time limits for the concerned material flow stages based on data analysis for electrical and control equipment of an oil and gas EPC project in the Russian Far East. The framework is then tested using a probabilistic Monte Carlo simulation. The results show a significant decrease in the storage cost, as an example of waste reduction. The framework provides a practical material management solution for EPC companies that minimizes non-value-adding durations and ensures a continuous material flow with continuous feedback and accountability loops.

KEYWORDS

Supply chain management, design science, flow, integration, waste.

INTRODUCTION

Construction projects are getting more complex, uncertain, and quick with a growing competitive market. This is coupled with an increased client's demand for lower project costs and faster project completion. In the specialized engineering, procurement, and construction (EPC) oil and gas industry, the monetary value of procurement equates to more than engineering and construction combined where the cost of supplies and equipment accounts for roughly 60 to 70 percent of the overall direct cost of construction (Patel & Vyas, 2011). Traditional construction industry material management practices are push systems that depend on pre-set deadlines for releasing work into the following activities (Alves, Tommelein, & Ballard, 2006). As a result, these processes have typically been associated with ineffective results including large inventory buffers, cost overruns, lower safety standards, or even a lack

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of necessary items on site. This is mostly due to the fact that the material operations are frequently separated from the real workflow and dispersed across various departments (Arbulu et al., 2005). For instance, the planning team is in charge of creating baseline schedules that drive procurement operations, but the procurement team is responsible for making sure that items are on-site when needed.

Offsite and onsite material logistics are the two primary divisions of construction logistics. Offsite material logistics are dependent on numerous companies cooperating in the form of a network with the goal of moving material efficiently to cut costs and time and increase customer value (Hamzeh et al.2007). However, because temporary facilities are frequently housed on-site, onsite material management tries to lessen site congestion (Said & El-Rayes, 2013). Moreover, by designating places for resource delivery and optimizing storage, onsite material management tends to decrease non-value-adding material transportation (Thomas et al. 2005). Offsite material management received a lot of attention in the literature. For instance, the use of the Kanban system was highlighted by Arbulu et al. (2003). The idea of supplier Kanban is to replenish the site with a small selection of limited range, made to stock products. They discussed the positive effects of this process-driven lean strategy on productivity and time reduction and concluded that ordering small quantities rather than large batches is essential for the strategy's success. They also suggested a new position called a supply chain integrator to concentrate on the value stream of the supply chain. Other initiatives to connect supply and manufacturing have been made. As an example, Arbulu and Ballard (2004) used a web-based tool incorporated with the Last Planner system to reach this goal. This is accomplished by using that technology to manage daily production in order to improve workflow dependability and reduce demand fluctuation. Arbulu et al. (2005) differentiated themselves by using lean tools and concepts like Kanban and pull systems based on a just-in-time approach as well as Standard Procurement System (SPS) Production Manager and SPS Material Manager as software tools to improve the dependability of production level workflow and material supply. Hamzeh et al. (2007) also approached the issue differently by putting more emphasis on logistics centers. They emphasized that supply will be highly variable because it depends on hazy construction schedules. This will result in mismatches in supply and demand, driving up costs and lengthening processing times. Based on that, they used simulations to demonstrate the potential benefits of logistics centers in dealing with supply changes and portrayed these facilities as superior options to site inventories due to the issues the latter have.

On-site material logistics, however, did not receive as much attention in the literature. In order to address this issue, Ghanem et al. (2018) made the case that prior studies only treated the site storage area as the final destination of supplies, failing to account for the possibility that issues would arise when moving goods to the actual construction site. Congestion on the site is a drawback of poor site material management, which will harm worker productivity and safety measures (Singh 2010; El-Gohary & Aziz 2013). Furthermore, by examining elements that are associated to productivity, Seppänen et al. (2016) examined how onsite logistics will impact worker productivity. In order to examine the impact of onsite material management on building projects, Patil and Pataskar (2013) applied inventory control approaches. They discovered that the inability to get materials on site in a timely manner is one of the main reasons for project variation, accounting for 5% of all project variations. They suggested implementing a reward system to encourage staff employees to sign up for construction material management training, so they become aware of material planning and scheduling at every step. Additionally, they suggested adopting ABC and Economic Order Quantity analyses for annual inventory control. The former is a method of inventory management that categorizes items based on their importance and is also known as Pareto Analysis or the 80/20 rule. The latter is a mathematical formula used in inventory management that takes into account the cost of ordering, the cost of holding inventory, and the demand for the product to determine the optimal order quantity that minimizes the total cost of ordering and holding inventory. Abou Dargham et al. (2019) sought to apply lean thinking to create, simulate, and model an efficient and dynamic site plan that will result in a seamless flow of materials on site, minimizing time and expenses. By using a pull-based supply chain of Glass Reinforced Concrete units and integrating some process activities, the results indicated a 16% decrease in the overall cost and a 15% reduction in the overall simulation time compared to the base model of the process under consideration.

It becomes evident that the application of lean concepts is key to eliminating the waste embedded in the material flow processes and reducing cost overruns and schedule delays. However, no study was found to explicitly focus on the application of lean concepts to improve the overall material management process and its impact on project performance, in particular in the specialized oil and gas EPC industry. By analyzing real project data, this study aims to identify the bottlenecks in the material management process of EPC oil and gas projects and develop a framework for a lean material management process relying on just-in-time delivery and pull system.

METHODOLOGY

The objective of this study is to develop a framework that can be applied by EPC contractors to reduce the waste embedded in the material management process of oil and gas EPC projects. This is achieved by following the design science research methodology. Namely, the problem is first identified by surveying the conventional flow of material along with the material management procedures of an international EPC contractor. The material management procedure is a set of guidelines and steps that defines the sequence of material flow from suppliers bidding stage up to delivery and handling on site; it also defines a set of key documents issued with regards to each stage of material movement. Data corresponding to each of the material flow involved stages of an oil and gas EPC project executed by the same contractor was extracted from multiple delivery reports exported from the Site Material Management System (SMMS). This system is a tool used to track material delivery, receipt, and issuance. In particular, the extracted data corresponds to the electrical and control equipment installed in an electrical substation of and oil and gas project in the Russian far east and include key dates in the flow of material, which provides an overview of the material management process. The dates were used to estimate the durations of each stage. Following that, an analysis was conducted on these durations and compared with the baseline schedule to identify the bottlenecks and the waste embedded in the process. A framework that targets those bottlenecks was then developed. Finally, the framework is tested on the project data using a probabilistic Monte Carlo simulation to show the magnitude of storage cost reduction as an example of waste minimization providing an illustration of the optimized material management process.

DATA COLLECTION

In a typical EPC project, the process of material management includes five main stages: bidding, manufacturing, shipping, storage, and erection/installation. Figure 1 shows the flow of material starting from the receipt of the material specifications from the Client up to their onsite erection or installation; each stage is mapped along with its responsible manager(s) and their interface with other functions managers. A solid line represents a direct reporting protocol, and a dotted line represents an indirect reporting protocol; for instance, in email communication terms, a solid line reflects “from / to” email communication(s) and a dotted line reflects a “cc” in an email communication. Stage 1 starts when the contractor prepares and sends requests for quotation (RFQs) to the potential approved suppliers (vendors); this process is directly managed by the procurement manager (PRM). Upon receipt of RFQs, the suppliers compile and submit to the contractor their technical and commercial offers; these undergo a thorough review process (i.e., bidding negotiation and technical clarifications) that allows the contractor to identify the best bidder technically and commercially. Once a bidder is selected, the contractor issues a purchase order (PO) to the supplier to start manufacturing, signaling the end of Stage 1. The bidding negotiation process is managed by the PRM and supported by the Engineering Manager (EM).

The contractor, being responsible for the material, deploys resources to the supplier premises to ensure the quality of the material. Upon the completion of the manufacturing stage, the contractor conducts routine testing and issues an inspection release notice (IRN) to declare the material is of good quality, signaling the end of Stage 2. The supplier then prepares the material for shipping and requests the contractor's approval to ship, which is usually in the form of a shipping release note (SRN). Stage 3 corresponds to the shipping stage; the material is shipped through regulated logistics routes (e.g., sea freight, air freight or land freight). Upon receipt on site, the contractor checks the quality of the received material, and the site team issues a material receipt voucher (MRV) and transfers the material to the site store. The material remains in store until the responsible subcontractor requests it; the store then releases the material through a material issuance voucher (MIV), signaling the end of Stage 4. Once an MIV is issued, the material is cleared to be erected on site.

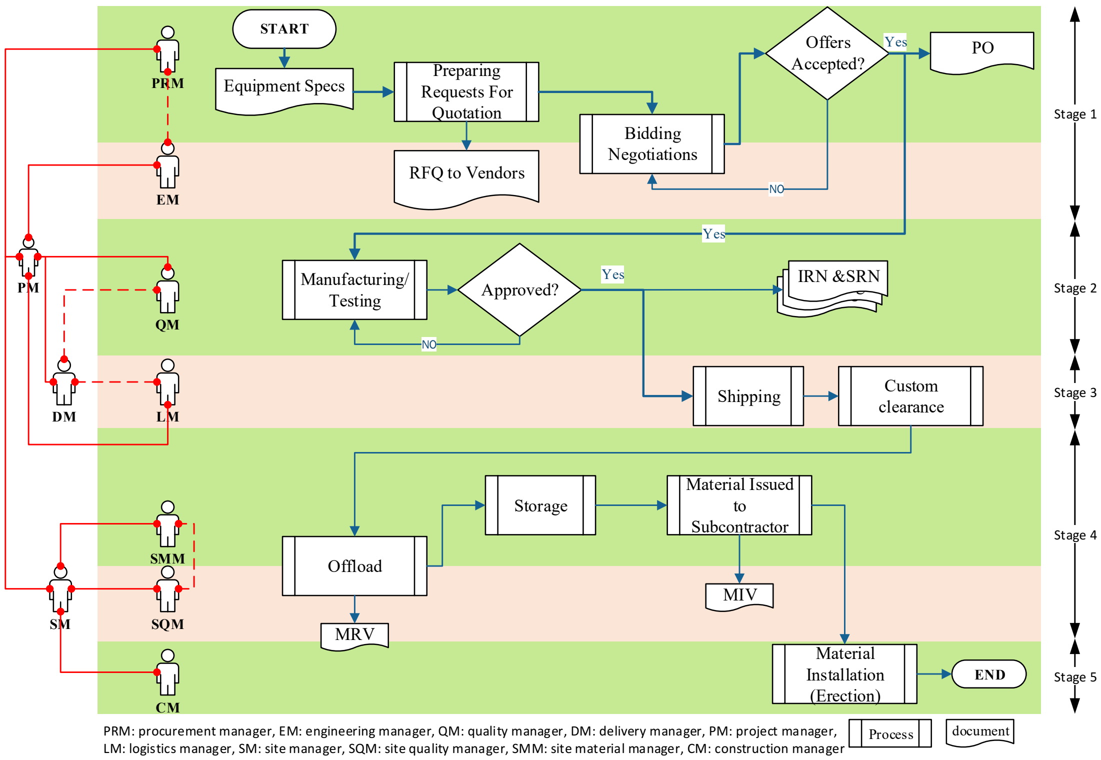

Figure 1: Material Management Process Flow Chart

To illustrate the waste embedded in the material management process, data was collected for 147 equipment installed in the electrical substation of an EPC oil and gas project in the Russian Far East. These were selected because they are tagged items that can be tracked efficiently. The selected equipment include electrical transformers, high voltage switchgears, uninterrupted power supplies (UPSs) and low voltage power panels, and cabinets for distributed control system (DCS), emergency shutdown system and fire and gas system. For each equipment in the substation, the dates corresponding to the RFQ, PO, shipping, site receipt, and erection milestones were extracted to calculate the duration of each stage in the process. The averages of these durations are illustrated in Table-1.

Table 1: Collected Data

Stage	Average Duration (Days)
Bidding	26
Manufacturing	71
Shipping	73
Storage	239

DATA ANALYSIS

The collected data show an alarming waste in the contractor's material management process. The root cause analysis of this data revealed three major bottlenecks. Starting with the bidding stage, an average of 26 days is a long time considering that the suppliers are familiar with the equipment and are able to submit the techno-commercial offers in less than two weeks. After a root cause analysis of this waste, the delay in this process is found to be caused by the heavy bureaucracy in the communication protocol whereby each revision of the offers must go through a lengthy approval process although the technical aspects are not time consuming (this is the first bottleneck). The second waste is illustrated in the manufacturing stage which takes up to 70 days on average. The analysis revealed that the equipment goes through quality checks prior to shipping from the supplier, which results in a substantial amount of rework to rectify the contractor's comments as the contractor inspects the equipment post-manufacturing (this is the second bottleneck). The shipping stage is considered within limits given the project's location.

The third and major waste, however, is manifested by the storage (idle) time on site (i.e., 239 days). To better analyze this waste, the progress of material arrival to site (i.e., cumulative percentage of total metric tonnage as a function of actual dates) is plotted along with the planned erection progress and the actual erection/execution progress of material (Figure 2). First, the figure shows a large gap between the material arrival and its planned erection. It could be argued that during the year between April-2020 and April-2021, the COVID-19 pandemic had a major influence on the workflow (the flow of both construction material and construction crew) which was the main cause for the piling of material at this time and also in pushing the execution of the project. However, this does not negate the fact that the erection was planned to take place starting Apr-2021 while the material arrival to site started in Apr-2020. This means that the equipment was going to be idle in the warehouse according to plan and that the erection activities were planned independently from the delivery plan. In other words, the procurement function's key performance indicator (KPI) being independent from the construction progress, there was no added value in delivering the equipment in Apr-2020 while the installation is only needed in Apr-2021, which indicates a major flaw in the management process (this is the third bottleneck). By analyzing the storage inventory area over time, it was found that the maximum inventory floor area was about 500sqm, which indicates the need for a storage facility for this substation to accommodate that area. Another observation from Figure 2 is the gap between the planned erection and the actual execution in terms of dates and durations as well (i.e., the planned duration is 81 days and the actual duration is 244 days), which can be traced to many intertwining factors. The actual execution matches with the planned execution, both of which are a year into the pandemic. However, during the pandemic, a significant shortage of workforce and material was experienced on site (although the case study equipment were already on site prior to the pandemic shutdowns, a lot of other material were obstructed). Therefore, the work that was supposed to be executed during the pandemic was heavily affected, and consequently, by Apr-21 although the erection works of the case study equipment commenced within planned time, priorities have changed due to the work obstructions during the pandemic and the pace of execution could not keep up with the plan. Another reason for the execution deviation can be traced to the manpower mobilization shortages from subcontractors due to financial issues.

To further illustrate the negative repercussions of the inventory waste, the storage cost is calculated. Based on actual storage cost data, and the fact that the selected equipment contains high quantity power electronics that need to be kept in a heated and well-preserved warehouse, the average cost of power requirement to preserve 1m^2 of floor area in a site warehouse in the project site in the Russian Far East was found to be \$1.55/m^2 per day. This cost covers the electrical power, manpower, and preservation costs. Considering each equipment floor area over its storage period, the total power cost to store all the equipment for their respective storage durations is found to be around \$204,000. In fact, the analysis revealed that this range of storage duration is very common due to two main reasons. First, given that material delivery to site is the main milestone to claim payment from client, contractors tend to push material to site as soon as they can to collect cash payments. The second major factor is that site management and site material management are under pressure to handle piling quantities of arriving material whether these are needed at that time or not. This is mainly because the delivery manager and procurement manager's KPI is to deliver the material to site as soon as possible since they lack a direct reporting protocol with site management. It is noticed that a recurring theme in the bottlenecks is the fact that each function manager acts to achieve their KPI on priority, and sometimes in isolation, without consideration to other functions which leads to a local optimization. Therefore, any attempt to improve the flow would not be as effective without changing the KPIs.

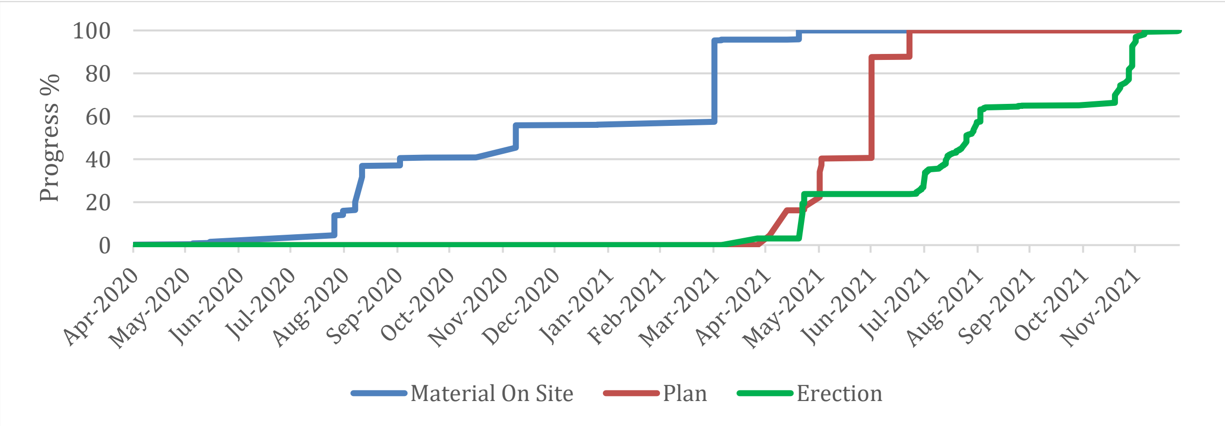

Figure 2: Material Delivery Vs. Erection Plan (measured in metric ton)

DEVELOPED FRAMEWORK

Based on the analysis of the data collected, three bottlenecks are found to impede the flow of material and its management process: the bidding bottleneck, the manufacturing bottleneck, and the storage bottleneck. These are viewed to negatively impact the project performance and are a critical indication for a substantial needed process improvement. The proposed framework is based on a pull system and a just-in-time material flow to reduce the process waste by introducing changes to the responsibility matrix and setting time limits based on data analysis. Namely, an enforceable timeline is introduced to managerially deal with each bottleneck. The timeline is determined based on oil and gas EPC industry best practices and may change depending on the industry and type of equipment/material. Starting with the bidding process, the timeline is set at 14 days with continuous communication between the engineering function and the procurement function and monitoring of the suppliers. This time limit is based on the activities of procurement in this project (2 days for floating the request for quotation to suppliers, 5 days for suppliers to compile and submit their offers, and 7 days for reviewing the offers and issuing purchase orders). Any delay in this process will be monitored by the project manager. Then, the manufacturing process timeline is set to 30 days. As described in the analysis section, a lot of the manufacturing time waste is due to rework resulting from the comments received during the inspection stage. Finally, the storage process timeline is set to be in the range of (0 to 7) days; this process is the most challenging bottleneck in the material flow due to the prolonged idle times of material in the warehouse. To this end, a pull system is implemented to regulate this process by signaling to the logistics teams the shipping date of the equipment that ensures its arrival at the site by the time it needs to be installed.

Moreover, the proposed framework includes changes to the responsibility matrix to ensure that the reporting structure supports a collaborative effort rather than being solely based on the achievement of individual milestones. Figure 3 illustrates the updated responsibility matrix and the newly introduced lines of communication (illustrated by solid lines) between different functions managers in addition to introducing the durations allowed to several activities to guide the process and make it more systematic. Namely, the proposed framework introduces the following changes:

- Adding a direct communication line between procurement manager and engineering manager for bidding process.
- Adding a direct communication line between delivery manager and quality manager for expedited manufacturing and testing at vendor sites.
- Adding a direct communication line between site material manager and site quality manager.
- Adding an indirect communication line (illustrated by dotted line) between site manager and procurement manager to initiate the procurement process in a timely manner.
- Adding an indirect communication line (illustrated by dotted line) between site manager and logistics manager to ensure material is delivered within a week of construction readiness based on the schedule.

To ensure the framework is followed and any deviation is escalated and consequential, new KPIs are introduced:

- Procurement manager: ensure the bidding process is done within 14 days - accountable for any excessive time.
- Delivery manager: ensure manufacturing is done within 30 days - accountable for any excessive time.
- Logistics manager: ensure delivery within 60 days.
- Site manager: timely signals to procurement and logistics (percentage)

Moreover, to maintain a feedback loop for any material that exceeds the 7 days limit, a root cause analysis must be conducted and reviewed by the site manager. However, given that the KPIs are not reviewed regularly, the material flow process needs to be monitored in the weekly inter-disciplinary meetings and to be continuously signaling to function managers. This process can be maintained using a frontend user friendly interface that takes the inputs from expediters or project engineers and sends alert signals to responsible managers based on the following questions represented in Figure 3:

- Are offers received and reviewed within 14 days?
- Is the shipping schedule within 60 days?
- Is the delivered equipment ready to be installed (logistics input)?
- Is equipment spending more than 7 days in the store?

The frontend interface will derive its protocol from Figure 3 and is illustrated in Figure 4.

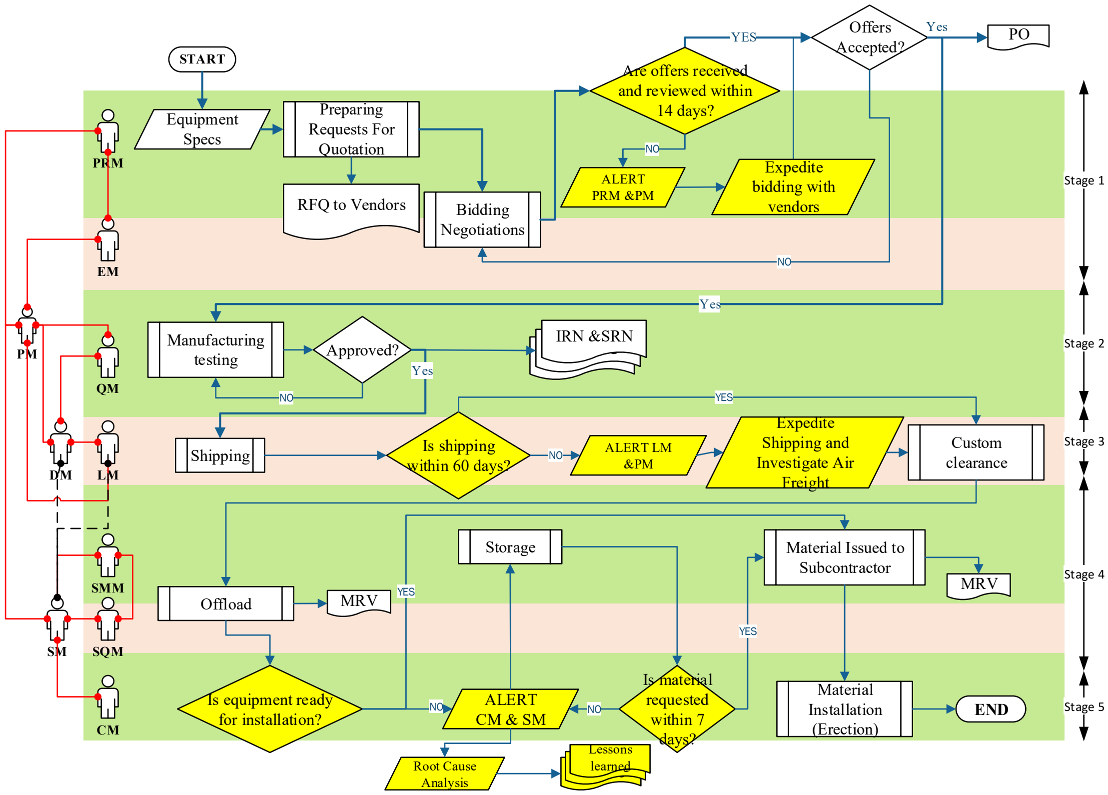

Figure 3: Flow of Material in the Proposed Framework

The input to the interface illustrated in Figure 4 is under the responsibility of the quality engineer, package engineer or material controller. The alerts will be sent automatically when the dates conflict with the set time limits. The alerts will be in the form of high priority emails to the respective function manager and will be raised in the weekly meetings. The number of alerts will be a key measure to determine the performance of each manager against the proposed KPIs.

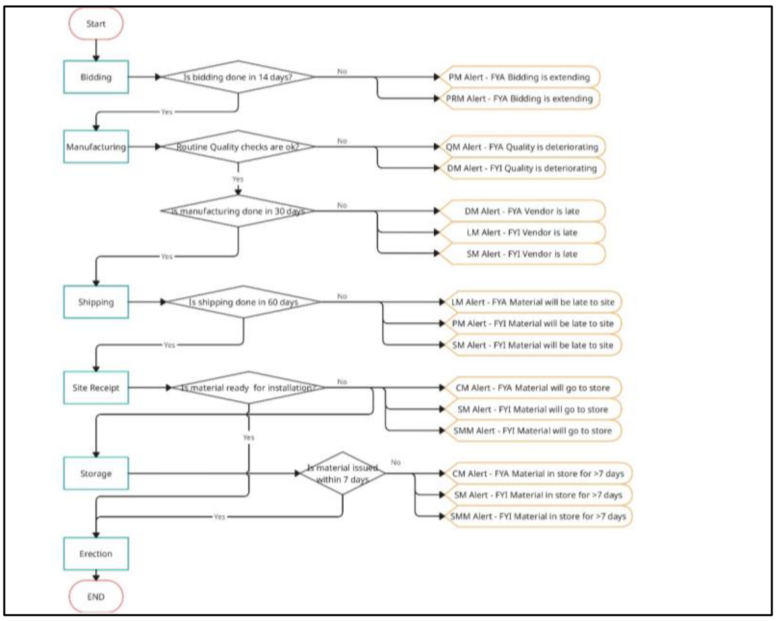

Figure 4: Frontend Interface for Material Tracking and Alerts

APPLICATION OF THE PROPOSED FRAMEWORK

To illustrate the enhanced material management process, the proposed framework is applied to the project data to show the magnitude of storage cost reduction (as an example of waste reduction and improved performance). To this end, a probabilistic model was built to measure the change in storage cost. The model considers an ideal scenario where the flow of material is not interrupted and the material arrives at site on time, and a worst-case scenario where the material remains in store for 7 days. The analysis was conducted using MS Excel and Palisade @Risk probabilistic tool. To check the effects of the proposed framework on the storage cost, the proposed system assumes that the material will ideally not spend any time in store, and if it does, it should be in storage for a maximum of 7 days. This was represented as a discrete probability density function with an 80% probability that the equipment will be erected within the same day of arrival without any time at store and a 20% probability that the equipment will be at the warehouse for 7 days as a worst-case scenario.

Using the $/sqm estimation calculated from the actual data, the output of this analysis is the summation of the storage cost for all items. This output is compared to the original storage cost of $204,000. The simulation was done using a Monte Carlo Simulation for 10,000 iterations. The results of the simulation for storage costs are illustrated in Figure 5.

Figure 5: Simulation Results for Storage Costs

Figure 5 shows that there is a 90% probability that the storage cost will be less than $1,800. This figure represents a massive improvement compared to the original cost of $204,000. The simulation was repeated at different test conformity levels (50% and 30%). The results of the simulation are summarized in Table-2 and show the expected storage cost with a probability of 90%.

Table 2: Storage Cost Simulation Results

Conformity Level	Storage Cost at 90% Confidence
80%	$ 1710
50%	$ 3511
30%	$ 4489

The proposed system redefines the warehousing strategy and ensures equipment remain in the warehouse for the minimum days. This is almost a total elimination of the inventory waste in the warehousing system. Another important improvement can be noticed at the level of inventory management. The previous analysis showed that the inventory in the warehouse kept piling up for almost a year until it reached a maximum of about 500sqm floor area in the warehouse. Based on the new proposed framework, an inventory model was built considering the worst-case scenario of all items spending 7 days in the store, the inventory curve is shown in Figure 6.

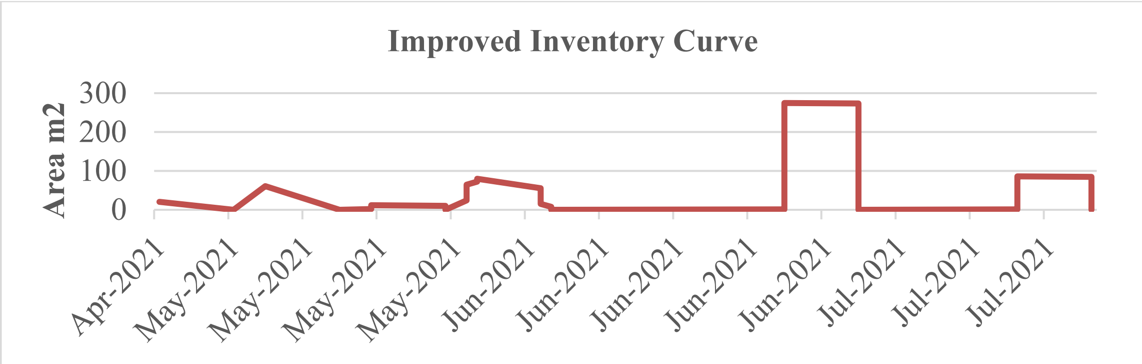

Figure 6: The Improved Inventory Curve

Figure 6 illustrates that the inventory is levelled at about 80sqm and keeps on emptying from the warehouse without piling up. This is a very good indicator that the system is effective in eliminating inventory waste. A spike is observed in June-2021, this is due to a large delivery lot. Although this would need a warehouse, it could be mitigated by renting space in the available warehouses on site to avoid the need for a new warehouse. For the other inventory peaks (May-21) the scenario can be eliminated by using other warehouses or simply by keeping the material in the truck for a couple of days to reduce handling cost and storage cost.

DISCUSSION

The simulation results provide an example of waste reduction as an illustration of the improved performance of the material delivery and management process. The simulation model derives its variables from the set time limits; these are project-specific and, therefore, are not rigid. Namely, the location of the case study was the driving factor in setting the time limits. The proposed framework, however, can be applied to other EPC projects since the material flow process is similar, but with necessary adjustments to the time limits and the KPI's derived from them. Additionally, the results illustrate an ideal scenario where unforeseen conditions are not affecting the erection of material. For instance, one of the reasons for the prolonged erection duration in the case study (244 days) is the breakout of the Covid-19 pandemic and lack of workforce on site. Should the proposed framework have been in place at that time, it would have helped in mitigating the delays and facilitating the implementation of a quick mechanism to compress the schedule due to the accountability loops. Moreover, beyond improving project performance in terms of schedule and cost reduction, the smooth and continuous flow of material is viewed to also ensure less material handling and congestion on site, therefore it is expected to improve the safety performance. However, a deeper investigation of these impacts presents an interesting future research opportunity.

CONCLUSION

The construction industry is witnessing an increased client's demand for a lower project cost and a faster project completion. In an EPC project, the monetary value of procurement contributes to more than engineering and construction combined. However, material management is yet to evolve from the conventional push system to a more efficient one. Following an analysis conducted on real EPC project data, the study shows that the flow of material in a conventional material management process is plagued with excessive waste. In-depth analysis of the waste embedded in each stage resulted in the identification of three major bottlenecks in the bidding, manufacturing, and storage stages. Accordingly, a framework based on a pull system and a just-in-time material flow is proposed. The framework aims to reduce the various waste embedded in the process by introducing changes to the responsibility matrix and setting time limits based on data analysis. Namely, an enforceable timeline is introduced to managerially deal with each bottleneck. The framework is tested using a probabilistic Monte Carlo simulation. The results show a significant decrease in the storage cost, as an example of waste reduction, providing an illustration of the enhanced material delivery and management process. The framework provides a practical solution to EPC companies that minimizes non-value adding durations and ensures a continuous material flow with continuous feedback and accountability loops.

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A THREE-LAYERED APPROACH FOR A LEAN SUBCONTRACTOR PROCUREMENT PROCESS

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ABSTRACT

It is generally recognized that subcontractors execute significant parts of construction works. This makes the subcontractor procurement process − from packaging to delivery method selection, budgeting, candidate selection, and so on − a cornerstone for the successful completion of construction projects. While the focus of the extant literature has been mainly steered towards the process of subcontractor selection and its related criteria, little emphasis has been placed on the procurement process itself and its implementation by general contractors. The main purpose of this paper is to develop a comprehensive lean methodology that may be applied by general contractors to improve subcontractors' procurement processes. To do so, a three-layered approach is proposed involving the realignment of steps within the process, the application of the choosing-by-advantages methodology, and the introduction of a digitalized subcontractor rating program. Then, the proposed approach is tested on a typical subcontracting procurement process adopted by a well-established construction contracting firm in the Middle East. Results show a significant reduction in the overall duration of the subcontractor procurement process. The offered methodology is viewed as a roadmap that can be generally adopted for reducing rework, eliminating waste, and enhancing the subcontractor selection methodology.

KEYWORDS

Lean construction, standardization, process, supply chain management.

INTRODUCTION

It is widely recognized that general contractors look to specialty contractors, or subcontractors, to perform specific tasks on construction projects. Hinze and Tracey (1994) mentioned that, particularly in building projects, it is common for 80-90% of the work to be performed by subcontractors. Subcontractors may provide specialized trade work such as painting, carry out specialized services such as electrical and mechanical, or provide labor services such as skilled craftsmen (Mbachu, 2008). Additionally, specific design works may be subcontracted to specialized firms. This reliance on subcontractors is rooted in several reasons. Bennett and Douglas (1990) argued that tasks in construction are specialized in such a way that no one firm can perform them all; therefore, many specialist contractors with specific expertise are required to meet the industry's complex demands. Additionally, Hsieh (1998) suggested that general contractors use subcontracting to allow the downsizing of their firms and to ensure better handling of unstable market conditions. Furthermore, operations of the average general

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contractor are not sufficiently extensive to afford full-time employment of skilled craftsmen in each of the several trade classifications needed in the field, nor is it feasible for these companies to own, operate, and maintain specialized equipment that may have only limited use during a project, as presented by Arditi and Chotibhongs (2005).

Typically, in building construction, there is a need for involving many specialized trades; this dictates the extent to which work packages are subcontracted and, therefore, leads to general contractors initiating frequently one or more subcontractor procurement process. Given the time-limitation characteristic of construction projects and the importance of making informed decisions within short time frames, the application of lean principles can be beneficial in ensuring their success from time, cost, and quality perspectives by facilitating the selection of the right subcontractor to execute the works. This study aims to develop a comprehensive lean methodology that may be applied by general contractors to improve subcontractors' procurement processes by reducing the overall process duration, limiting rework, and improving the quality of the decision-making approach.

LITERATURE REVIEW

One of the most significant factors affecting the costs of construction projects and the entire construction industry is the efficacy of subcontracting procurement processes (Yin et al., 2014). In the extant literature, the focus has been mainly steered towards the process of subcontractor selection and its related criteria, subcontractor rating methodologies, and the relationship between general contractors and subcontractors. For instance, according to a study by Arditi and Chotibhongs (2005), the process of bid shopping by general contractors is one of the problematic issues in subcontracting and may cause detrimental consequences on the overall performance of the project. Possible solutions are therefore presented based on the input of surveyed professionals, including owners requiring general contractors to provide bid listings and subcontractors refraining from providing contractors who shop bids with quotations. Other issues in subcontracting practices are also addressed in their study including payment timeliness, provision of construction insurance, site safety issues, and productivity issues (Arditi & Chotibhongs 2005). Ulubeyli et al. (2010) discussed the subcontractor selection practices of Turkish contractors in international construction projects. Their study reports that, although most contractors employ previously known subcontractors, no systematic processes nor models are put in place as a means for making an optimal selection. It is also highlighted that subcontractors are frequently selected based on the decision-makers' own experience rather than via a selection process and suitable evaluation technique (Ulubeyli et al., 2010). In another study that forms part of the ongoing discussion around partnering and subcontractor selection, Hartmann and Caerteling (2010) discusse price and trust as subcontractor procurement mechanisms and explore how the interaction between the two is important in the selection of subcontractors. Abbasianjahromi et al. (2013) proposed a model for subcontractor selection based on the fuzzy preference selection index. The value of their model lies in eliminating the weighting criteria phase in selecting the optimal subcontractor where weighting attributes is a challenging task. Polat et al. (2015) used the genetic algorithm technique as a methodology for selecting subcontractors for all work packages in a construction project considering time, cost and quality performances. El-Khalek et al. (2019) identified subcontractor prequalification evaluation criteria and their impact on project success. Among the evaluated criteria, on time delivery of materials, failure to complete contract due to financial problems, subcontractor's difficulty in reimbursement, reputation, and tender price were found as the most influencing ones.

On the other hand, the implementation of the choosing-by-advantages (CBA) as an alternative method of subcontractor selection has been heavily explored in the construction industry literature. Notable recent publications include Demirkesen and Bayhan (2019) in which twelve factors for evaluating alternatives are presented and connected to a seven-step CBA procedure. The result is a selection which ranks highest importance of advantages and lower cost of advantages. El-Kholy (2022) presents a rigorous analysis of the proposed technique using CBA and explores an illustrative case study for testing. It is concluded that the proposed methodology takes into account aspects of decision-making that are not considered in traditional methods and paves the way for further exploration in the literature. Limited studies are found to tackle the analysis of traditional procurement procedures and the presentation of innovative processes. Yin et al. (2014) presents a procurement process that is mapped against the seven types of waste which forms the basis of lean theory. It discusses how traditional procurement methods for subcontracting tend to bound opportunities for price negotiation, constructive contractor relationships, and the avoidance of future problems such as waste, risk in construction, and engineering interface (Yin et al., 2014). In an attempt to address this, a Lean Subcontracting Procurement Process (LSPP) is presented which is initiated by a subcontracting plan based on a seven-arrangement operation plan that is aimed at eliminating various types of waste in construction projects, and which involves four types of operating flows. The implementation of this LSPP in its collaborative nature resulted in cost reduction and shortened construction time (Yin et al., 2014). Suresh and Arun Ram Nathan (2020) discuss lean procurement in construction projects using the total interpretive structural modeling (TISM) approach to classify readiness factors and build a model which helps construction companies in India to begin the implementation of lean production. They focused on material procurement which is very similar to that of subcontractor procurement in construction sites. The model analysis identifies the techniques of awarding purchase contracts, checking material specifications, negotiating with suppliers, and subtracting the cost of material as the model's driving forces. The change of these four factors has gained importance in Lean procurement execution as they directly affect other sections of the organization.

The focus of the construction industry literature has mainly been directed towards the process of subcontractor selection, the criteria used in the decision-making process, and the drawbacks of these traditional methodologies. Little emphasis has been placed, however, on the subcontractor procurement process itself and its implementation by general contractors. This study presents an in-depth analysis of the steps involved in the subcontractor procurement process in a typical building construction project and proposes a three-layered approach rooted in the application of lean principles to achieve a shorter and more efficient process.

METHODOLOGY

This study follows the Design Science (or constructive) research approach which entails the creation of a solution for a practical field problem (Rocha et al., 2012). Namely, this study aims to propose a comprehensive lean approach that may be adopted by general contractors to reduce the waste embedded in the subcontractor procurement process. The problem is identified through direct observations of the subcontractor procurement process followed by a well-established general contracting firm in the Middle East. The solution artefact is developed through a multi-stage process that includes data collection, data analysis, and the proposition and evaluation of a three-layered lean subcontractor procurement process. In the first stage, data with respect to the steps followed during the subcontractor procurement process in three recent tower construction projects was collected through surveying procurement records such as internal communications, exchanges with subcontractors, and meeting records, and through discussions with team members that were involved in the projects of interest. For the purpose of this research, the three selected projects have been awarded following the design-bid-build approach to project delivery. This is important because, under more collaborative project delivery methods, the structure and the timeline of the procurement process would be completely different. The three projects are of similar value (around $70 Million) but with different scope of work. More importantly, these projects are relatively in the same location and were undertaken within the same timeframe; this is of particular importance in eliminating external factors such as the effects of economic instability on the decision-making process and consequently on the procurement strategy as a whole. The location of the projects is also of importance as it plays a major role in the availability of subcontractors to choose from. Accordingly, the current state of the typical procurement process followed by the general contracting firm is mapped along its corresponding data. Then, the analysis stage of the data collected allowed the identification of the waste embedded in the process and also unveiled opportunities for improvement. Finally, a three-layered process is developed and includes incorporating the CBA decision-making process and integrating lean concepts with digitalization techniques to form a comprehensive lean subcontractor procurement process.

DATA COLLECTION

The contractor's typical procurement procedure adopted on various projects, and particularly on the three building construction projects of interest to this study is explored by identifying and mapping the various involved stages of the complete process starting with a subcontracting plan and ending with a signed subcontract. The flowchart in Figure 1 reflects the current state map of the typical subcontractor procurement process and depicts its various stages along with the various departments involved, each according to its role within a stage. These include a total of 6 stages (sequenced horizontally, left to right) and involve several departments as well as external stakeholders (displayed vertically); particulars of these parties and their functions within the subcontractor procurement process are detailed in Table 1.

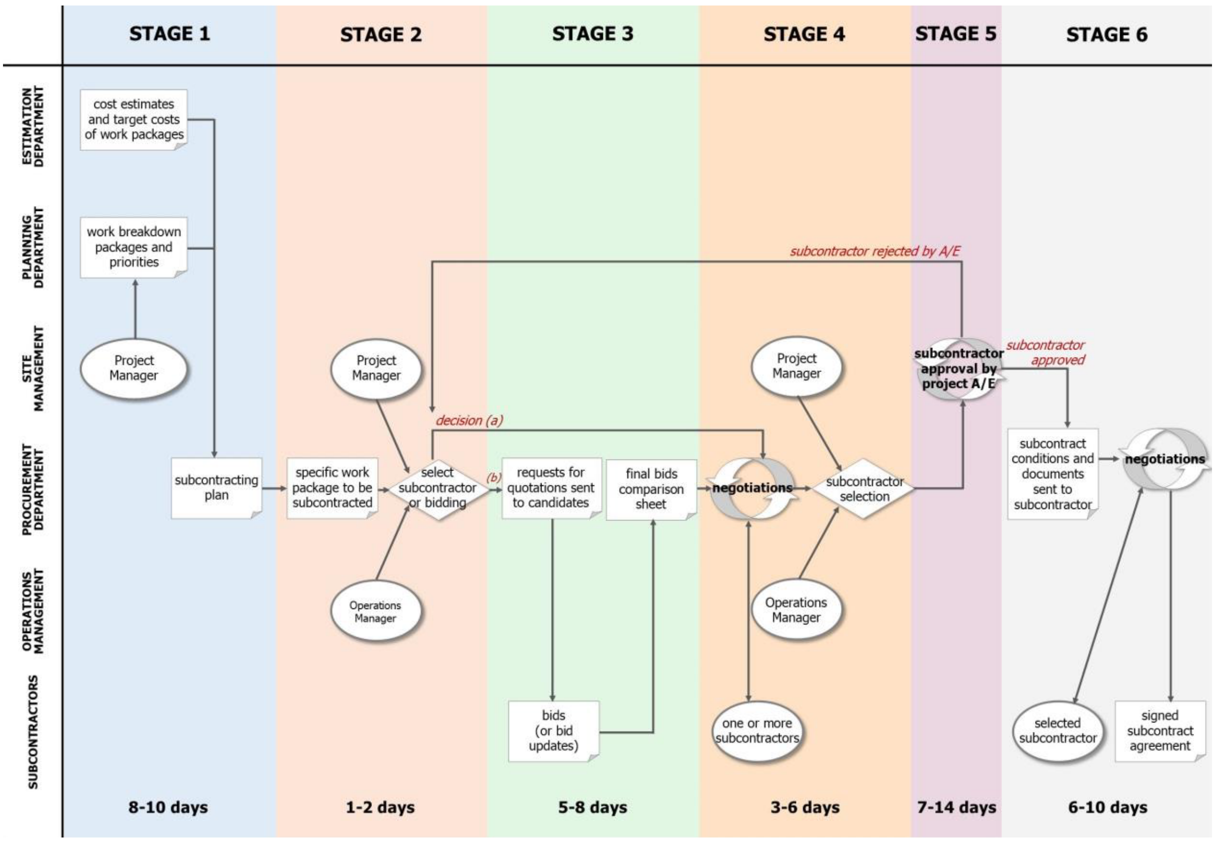

Figure 1: Flowchart of the Typical Subcontractor Procurement Process

The procedure is initiated in Stage 1 by a collaboration between the estimation and planning departments in direct coordination with the project manager and the procurement department, which produces a subcontracting plan that will form the starting point of any and all process initiation. Stage 2 is then started with a specific work package that comprises a target cost and a target schedule. It's important to note that, in this case, stage 2 is instigated purely based on the subcontracting plan and does not take into account any project delays or schedule changes. The procurement department shortlists a number of subcontractors who are suitable candidates for completing the subject works from whom they may or may not have received prices during the tender stage and presents them to the project manager and operations manager in a strategic decision-making meeting. During this meeting, a decision must be made on whether negotiations shall be made with a single suitable subcontractor (i.e., decision "a") or else to proceed with bidding (i.e., decision "b"). The former decision is normally a result of the scope complexity and characteristics of the subject work package, combined with the availability of specialized subcontractors in the market. The factors affecting the decision and the implications of the decision-making methodology will be discussed in subsequent sections.

Table 1: Parties Involved in the Subcontractor Procurement Process

Party	Internal/ External	Stages Involved	Main Role in the Process
Estimation Department	Internal	Stage 1	Provide information about the pricing strategy used during tender and the target cost of each work package to preserve planned profits.
Planning Department	Internal	Stage 1	Provide required information regarding the deadline for procuring a subcontractor for each work package (priorities) as well as the completion date for each work package.
Site Management Team	Internal	Stages 1, 2, 4, 5	Project Manager provides their opinion and guidance on the whole process concerning their preferences for the packaging of the works as well as specific subcontractor preferences. Site team is also in charge of the process of getting the A/E's approval on subcontractors (this may include iterations).
Procurement Department	Internal	Stages 1, 2, 3, 4, 6	Starting with a subcontracting plan, the goal is to ultimately produce a subcontract agreement with the selected subcontractor.
Operations Management	Internal	Stages 2, 4	Offer strategic planning, guidance, and judgment regarding subcontractor selection in line with the firm's business plan.
Subcontractors	External	Stages 3, 4, 6	Compile and submit bid prices and, if selected, provide their company profile for approval and, once approved, sign a subcontract agreement with the contractor.
Project A/E	External	Stage 5	Consent to the appointment of subcontractors.

In the case of decision (a) being made, stage 4 is initiated which will be discussed shortly. In case of decision (b), stage 3 commences with requests for quotations sent to candidate subcontractors. These candidates may have previously submitted their bids during the tender stage or may be newly invited. Once all bids have been received from the candidates, a bid comparison sheet is prepared showing an item-by-item comparison of the priced Bills of Quantities (BOQ), noting that some subcontractors may choose not to submit a bid for many reasons such as poor previous experience with the contractor, project location not being suitable, project scope being too risky for their business, and many others. Before making a final decision, stage 4 begins with a round of negotiations with either the selected subcontractor(s) from stage 2 or those whose bids were the lowest in stage 3. This step is purely commercial, whereby the price is negotiated in order to reach the target price; it may however be omitted if the presented bids already meet the target price presented at the beginning of the process by the estimation team. Once this step is completed or omitted a decision is made, and a subcontractor is selected with the guidance and judgement of the project manager and the operations manager.

Before proceeding with the subcontract preparation, and should the main contract conditions stipulate this, the subcontractor's details, profile, and previous experience are submitted to the project's Architect/Engineer (A/E) for their consent. Should the subcontractor be rejected, stage 2 is reinitiated in order to make a new selection. Otherwise, a subcontract is prepared and sent to the subcontractor for review and signature. Typically, a round or two of negotiations take place regarding the conditions of the subcontract, and, in rare cases, subcontractors may impose an addition to their price to bear the risks stipulated in the subcontract. Finally, once the contractor and subcontractor reach common grounds regarding the subcontract conditions, an agreement is signed, and the subcontractor proceeds with the works. The complete subcontractor procurement process, as presented in its current state and including all 6 stages, is found to take a minimum of 30 working days to be completed and a maximum of 50 working days, assuming that the first decision is (b) and that the subcontractor is approved by the project A/E from the first round.

DATA ANALYSIS

The collected data clearly show big room for improvement. Given the extent to which work packages are typically subcontracted on building construction projects, a total duration of 30 to 50 days per package could potentially cause major delays. Below are the various types of waste identified in the process:

The inherent push system based on which the initiation of stage 2 is made: The subcontracting plan, which is the basis for initiating a procurement process, is prepared in the first weeks of the project life. As such, it does not take into account any schedule and priority changes or the progress of procurement itself, which may cause a figurative inventory of packages that are not required to start just yet. Scope modifications, schedule delays, or other adjustments may require certain work packages to be procured in a sequence that is different from that of the subcontracting plan.

Major rework is embedded in the process, particularly with the subcontractor selection process. Holding two decision-making meetings with various parties, as well as having to restart the process of selection in case the project A/E does not give their consent are two major forms of waste. Additionally, leaving subcontract negotiations until the last stage also causes unnecessary rework; this could easily be avoided by providing the subcontractor with a draft agreement earlier on in the process to make them aware of its conditions.

The decision-making process is plagued with human error. With no specific decision matrix, it is purely based on the opinions of the procurement department, the project manager, and the operations manager. For instance, previous experience with subcontractors, a major contributor to the selection process, is not referred to or well-documented in order to be used as a benchmark.

PROPOSED THREE-LAYERED APPROACH

To address the identified flaws in this subcontractor procurement process, a three-layered approach aimed at reducing rework, eliminating waste, and enhancing the subcontractor selection methodology is proposed and is illustrated in Figure 2. The first layer involves a change in the way a new process is instigated as well as a simple realignment of processes at two levels of the procedure, namely the process of securing the project A/E's consent on the subcontractor and the process of negotiations of the subcontract conditions between the contractor and the subcontractor. With regards to the process initiation, and in order to address the issue of frequent changes in construction projects, a pull system by which work packages are only sent to the procurement department for action at the last responsible moment is proposed; this allows them to sign the subcontract before the works are due to be commenced (plus enough lead time to allow subcontractors to procure the materials needed). In addition to ensuring the right work packages are procured at the right time and with the most up-to-date project information, the adoption of this lean principle allows the workload to be pulled in such a way that ensures no package is procured too soon, and hence the possibility for abortive works is reduced.

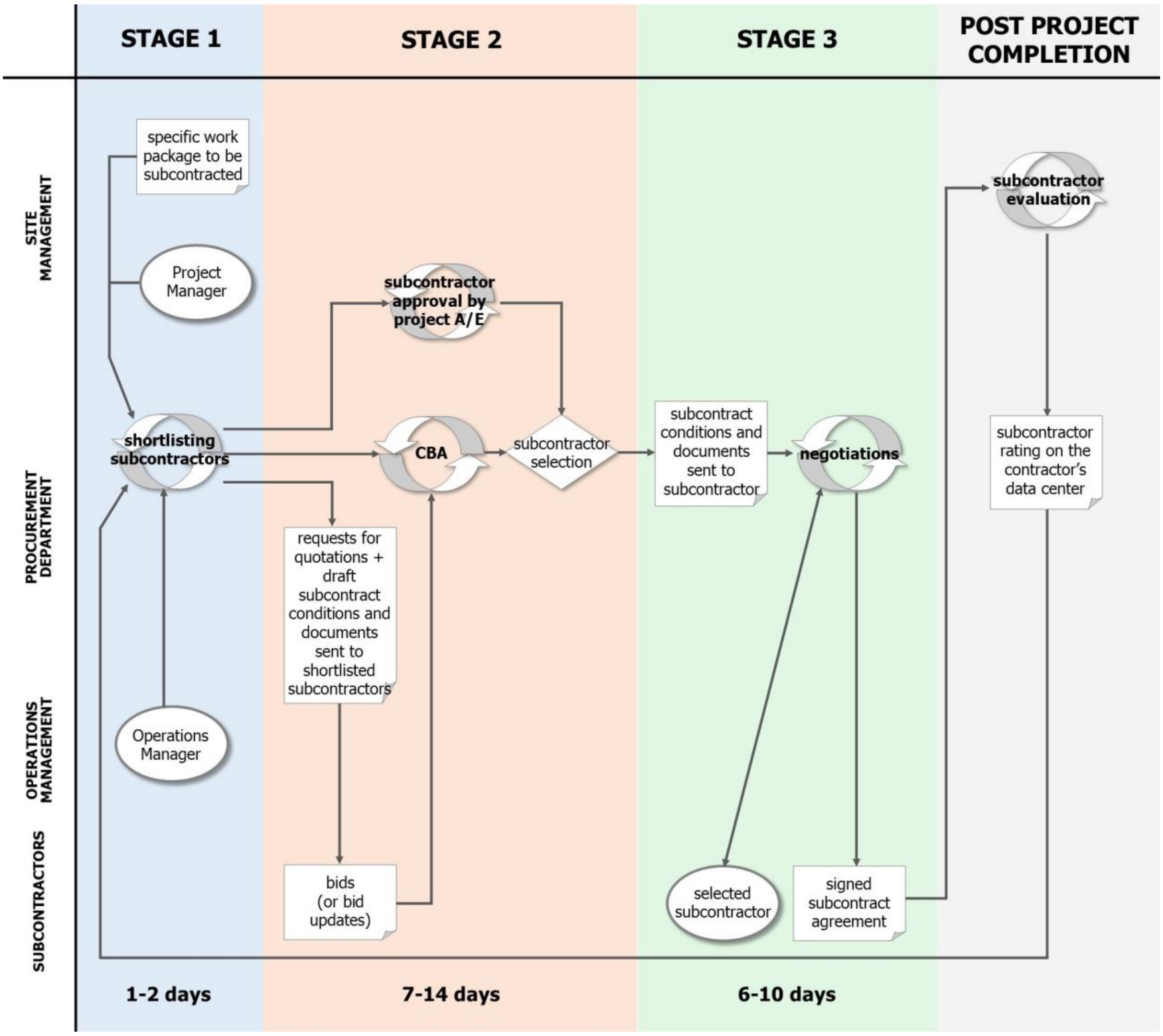

Figure 2: Proposed Three-Layered Subcontractor Procurement Process

In order to avoid possible rejection by the A/E after having invested time in selecting and negotiating with a selected subcontractor, it is proposed to submit for approval the details of shortlisted subcontractors from the optimized stage 2. By doing this, time is saved by initiating this process in parallel with the decision-making process of selecting a subcontractor in addition to avoiding rework in case consent is withheld by the A/E. At another level, it is also suggested to provide the shortlisted subcontractors with a draft of the subcontract conditions and documents along with the request for quotation in stage 3. This allows subcontractors to be aware of these conditions and account for any risks in their prices, hence avoiding disruptions in the process or possible price changes prior to signing the subcontract.

The second layer addresses the subcontractor selection phase of the procurement procedure. As discussed, the current state not only necessitates iteration by having two decision-making processes running at two different stages, but it also leaves much room for human error as it is purely based on opinion and advice, albeit being from professionals and stakeholders in the project. The choosing-by-advantages (CBA) is proposed as a method for enhancing the decision-making process by using multiple qualitative and quantitative criteria. The CBA framework proposed by El Kholy (2022) is proposed to be adopted as a means for enhancing the decision-making phase of the subcontractor procurement process. The main advantages of the CBA method are (a) its ability to accommodate the comparison of multiple alternatives (subcontractors in this case) over several factors, (b) its ease of use by creating a straightforward matrix structure using simple software which may be used with any work package on any project, and (c) reducing the possibility of human error of judgment through its scientific basis of calculation, which in turn reduces cycle time and minimizes the amount of coordination required between departments.

The third and final layer is related to the shortlisting of subcontractors and the use of historic data in such a manner that allows for continuous improvement and learning. An online-based subcontractor rating program within the contractor's Enterprise Resource Planning system is suggested in which data about subcontractors' expertise, contact details, as well as performance history is compiled. This stage requires project managers to rate subcontractors at the end of every project against a set of pre-determined criteria from technical, commercial, and time perspectives. The subcontractor rating stage takes place beyond the procurement process, long after the subcontract agreement is signed. It forms an integral part of the procedure enhancement by creating a feedback loop essentially based on the principle of continuous improvement. Namely, it paves the way for sustained benefits as a result of recurrently examining the performance of subcontractors and, in turn, the efficiency of the subcontractor procurement process itself. By having all this information readily available to the procurement department, a shortlist of potential candidates for the performance of any work package is easily created, which will form the basis for starting the CBA decision-making process as well as sending out requests for bids. This list of subcontractors may also be submitted to the project's A/E for approval in order to save time and reduce reiteration. It should be noted that this may not be accepted by all A/Es. However, by adopting the previously suggested rating system, one of the criteria could be the previous consent by A/Es to the specific subcontractor. As such, the shortlist will take this data into account by eliminating those that have previously been rejected by the specific A/E on the project.

DISCUSSION

The application of the proposed three-layered approach resulted in reducing the overall duration of the subcontractor procurement process from 30-50 days to just 14-26 days and in reducing the need for the involvement of many different parties. The subcontracting plan is now considered to have been completed prior to the initiation of stage 1 and the trigger for the procurement process becomes a specific work package requested by the site team in coordination with the planning department. The underlying reason is, as previously discussed, the application of a pull system that is based upon real-time project requirements, therefore allowing for better time management and reducing the need for rework.

The governing factor in determining the duration of stage 2 is the period stipulated under the main contract for the A/E's reply to submittal, assumed to be anywhere between 7 and 14 days typically. This is the longest of the durations among the three activities taking place simultaneously during this stage, namely (a) the request and receipt of bids from shortlisted subcontractors, (b) the setting up of the CBA framework, factors and determining criteria with their weights, and (c) the consent of the A/E. In this case, since a list of subcontractors is submitted (or in the case discussed earlier of the A/E rejecting this setup, the historical data will lead to the submittal of a subcontractor likely to be consented to by the A/E), the risk of rejection is very low, and rework is highly unlikely. As such, the longest among the durations of Stages 3, 4, and 5 of the conventional procurement process was adopted as the governing duration for Stage 2.

The final stage of subcontract conditions negotiations is considerably shorter than in the current state map since the subcontractor has already been made aware of them when requesting new bids in stage 2. By doing so, the subcontractor would have the opportunity to make allowances for the mitigation of any risks they deem necessary. While there will still be conditions and details to be negotiated at the final stage prior to subcontract signature, the extent of these will be limited to those of which the subcontractor deems completely unacceptable to them.

Finally, the proposed approach, having been developed based on a main contractor's adopted procedure in building construction projects, is particularly applicable to such projects. However, this methodology is indeed applicable to any project that is awarded following the design-bid-build approach to project delivery and that entails a need to go through a subcontractor procurement process. What makes it appealing in building types of construction is the high volume of work that is typically subcontracted, and which is commonly more extensive in building construction than other types of construction projects and where the number of work packages sub-let to specialty subcontractors is more sizeable, leading to many more instances of running the process.

CONCLUSION

Depending on the level of complexity and time limitation of the construction project at hand, contractors may decide to execute the various work packages of the project either in-house or with the help of subcontractors.The subcontractor procurement process is a complicated procedure involving input from different parties and encompassing several stages where decision-making takes place. Given the extent to which work packages are subcontracted on building construction projects, the selection of the right subcontractor and having a signed subcontract at the right time is of paramount importance. While the extant literature has thoroughly examined the issue of subcontractor selection, little emphasis has been placed on the procedure adopted by contractors to turn a work package into a subcontract agreement. This study aimed at closing this gap in the literature by examining a typical subcontractor procurement process of six stages, with potential judgement-related risks, and proposing a three-fold enhancement rooted in the application of lean principles to achieve a shorter, more efficient process. Namely, the proposed approach involves realignment of the steps within the subcontractor procurement process, coupled with the application of choosing-by-advantages methodology and a digitalized subcontractor rating program as a means for achieving a process with limited non-value-adding activities. The offered methodology is viewed as a roadmap that can be generally adopted by general contracting firms to reduce rework, eliminate waste, and enhance the subcontractor selection process.

The limitation of the study is that the process mapped reflects the typical process followed amongst general contractors of similar size undergoing building construction projects in the same region. It is recommended for future studies to have the same process studied with multiple contractors and on other types of projects such as infrastructure projects. Furthermore, while this study paves the way for examining the effectiveness of existing procurement processes adopted by contractors and how the application of lean principles can be of benefit, further research would be helpful in bridging the gap between available subcontractor rating criteria and digitalization by developing industry tools that allow the implementation of those criteria into an innovative subcontractor rating mechanism.

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CONSTRUCTION SUPPLY CHAIN PRODUCT DATA INTEGRATION FOR LEAN AND GREEN SITE LOGISTICS

Fabrice Berroir[1], Magdalena Pyszkowski[2], Omar Maatar[3], and Nico Mack[4]

ABSTRACT

Supply Chain Management using Construction Consolidation Centres, kitting and Third-Party Logistics were proposed to streamline material flows in construction and reduce costs. Studies also highlight potential mitigation of the environmental impacts of the Construction Supply Chain but, despite the climate emergency, these solutions struggle to become industry practice. Digitalization, especially with Building Information Modelling based processes, appears as a key enabler for this transition, but it is hindered by heterogeneous data between construction companies and suppliers (made of manufacturers and resellers). Therefore, semantic Digital Twins, that can use Product Information Management, and recent norms on Product Data Templates have been proposed, but they need to be studied through practical cases from both construction site and supply chain perspectives. Consequently, this study applies a Design Science Approach involving 3 pilot projects, a manufacturer and digital supply chain experts around the development of a proof of concept of a Digital Twin tool for Lean and green logistics in construction. We identify what limitations of classical technologies used in the pilots could be addressed by a Digital Twin, we define what product data is needed for such a use case, and we compare practical scenarios for sharing and storing this data.

KEYWORDS

Supply Chain Management (SCM), Logistics, Digitization, Digital Twin, Product information management (PIM).

INTRODUCTION

Inspired by Toyota Production System's Just-In-Time production and logistics, Supply Chain Management (SCM) is a key topic for Lean Construction since the years 2000 (Vrijhoef and Koskela, 2000; Arbulu and Ballard, 2004). The uncontrolled flows of materials in the construction sector cause many inefficiencies on site such as repetitive handling or losses, with a direct impact on productivity and costs reported by many authors (e.g., Mossman, 2008; Dakhli and Lafhaj 2018). Health impacts for workers are also considerable, for example the French health insurance office estimates that material handlings cause at least 48% of work-related accidents on construction sites (Assurance maladie, 2021). Lastly, the environmental impact of construction material flows is significant, with about 20-35% of all urban freight traffic caused by the construction sector in Europe (Brusselaers et al., 2020). In the Netherlands,

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27% of all greenhouse gas emissions in 2015 are attributable to construction logistics (encompassing infrastructure, buildings for construction companies and building materials supply). In the context of environmental emergency, the concept of Green Lean Approaches (e.g., Rosenbaum and Gonzales, 2012) requires these issues not be treated in isolation, since improvements in the productive process can also lead to reduction of environmental impacts. These considered, supply chain management and logistics are of prime interest.

In previous research, Vrijhoef and Koskela (2000) pointed out the "myopic control" of the supply chain in Construction. Practical solutions were proposed with benefits reported both from an environmental and from a productivity perspective. For example, Mossman (2008) reported building costs at 80% of industry benchmark and a 73% reduction in CO2 emissions of material transportations thanks to the London Construction Consolidation Centre. The concept of Construction Consolidation Centre (CCC) also called Construction Logistics Centre (CLC) has since become more applied/researched (e.g., Guerlain et al., 2019; Brusselaers and Mommens, 2022). This may be used in combination with kitting where the material is delivered in batches at the exact workspace resulting in a productivity increase (Elfving et al., 2010; El Moussaoui et al., 2020; Tetik, et al. 2021). Lastly, the logistics operations may be performed by a specialized Third-Party Logistics (TPL) operator as described by Ekeskär and Rudberg (2020). Despite some differences in scope, methods, or equipment, all the examples above are similar by the fact that (1) they break existing silos within the Construction Supply Chain, or between Construction Supply Chain and construction site(s), and that (2) digitalisation is stated as key when developing/deploying these solutions.

Therefore, this article aims to investigate product data integration from the construction supply chain for lean and green logistics. Specifically, it develops its practical implications for both construction sites and manufacturers.

LITERATURE REVIEW

The combined application of Building Information Modelling (BIM), Lean and Supply Chain Management can guide the whole sector towards improved procurement and execution performances (Le et al., 2018; Guerriero et al., 2018). While BIM does not only include geometric information, more and more data related to the processes and detailed product specifications are covered under standards such as the Industry Foundation Classes (IFC) (BSI, 2013). The BIM is complemented by the Digital Twin (DT) concept, which has the potential to enrich existing BIM data with dynamically sensed datasets, leveraging on real-time monitoring and the synchronicity of the cyber-physical bi-directional data flows (Boje et al., 2019). More specifically semantic-based digital twin applications promise the ability to link heterogenous datasets. This could be applied to link data silos between construction supply chain actors (manufacturers, resellers, etc.) and thus facilitate a shift towards BIM-and DT-based processes.

According to Peltokorpi and Seppänen (2022), Product Information Management (PIM) is a core component in achieving this shift. The study identifies use cases and proposes an applicable process for PIM where product data comes from manufacturer as 'standard' data and is enriched with 'instance' and 'process' data. Consequently, systematic PIM is stated as an essential part in the effort for lean construction. Notably regarding logistics, PIM allows better coordination of material supply using identification codes such as Global Trade Identification Number (GTIN) from GS1 (Daskalova et al., 2019) with tracking tools and linking product libraries and project data. To provide product data in a structured and standardized way, manufacturers need to know what information they should provide and how it should be presented. Hence, Product Data Templates are suggested (Meda et al., 2020). They are defined by product type based on ISO 23386 and ISO 23387 (International Organization for Standardization, 2020) in compliance with ISO 12006 and they enable the identification of properties and groups of properties. To maintain classifications and property sets, buildingSMART offers an online service called buildingSMART Data Dictionary (bsDD) (Buildingsmart, 2021). However, according to Peltokorpi and Seppänen (2022), “more practical research is needed to test the process and integration of the solutions”. Most notably, further research should study how to efficiently link product standards, instance and process information with BIM and test the applicability of product Data Templates from a supply chain and construction material provider’s point of view.

Consequently, this paper investigates how PIM and the Digital Twin concept can contribute to supply chain integration and logistics optimisation in construction. We assume that breaking data silos is a first necessary step to break decisional silos between the construction sites and their supply chain and that it will serve a lean and green perspective. We investigate in practice, from both the construction sites and the supply chain perspectives, how product data integration from the manufacturer could be used to support and upscale Supply Chain Management methods for reduced costs and environmental impacts of construction logistics.

METHODOLOGY

To cover practical implications and perspectives of product data integration from both sides of the supply chain, a Design Science Approach was chosen. With the participation of site managers from several case studies, a global construction product manufacturer and Supply Chain digitalisation experts, it aimed to develop a Proof of Concept (PoC) of a semantic Digital Twin for construction logistics optimisation. Therefore, this research was conducted as a use case of the Digital Supply Chain in Built environment group (Daskalova et al., 2019). Created from a memorandum of understanding between BuildingSMART and GS1, this consortium involved Construction Supply Chain companies to promote data driven collaboration.

The overarching research is tackled by the following questions (fig.1):

- Why Digital Twin and PIM are important for lean and green logistics on site? (Q1)
- What data is needed from the manufacturer to enable logistics optimisation? (Q2)
- How can this data be efficiently provided by manufacturers? (Q3)

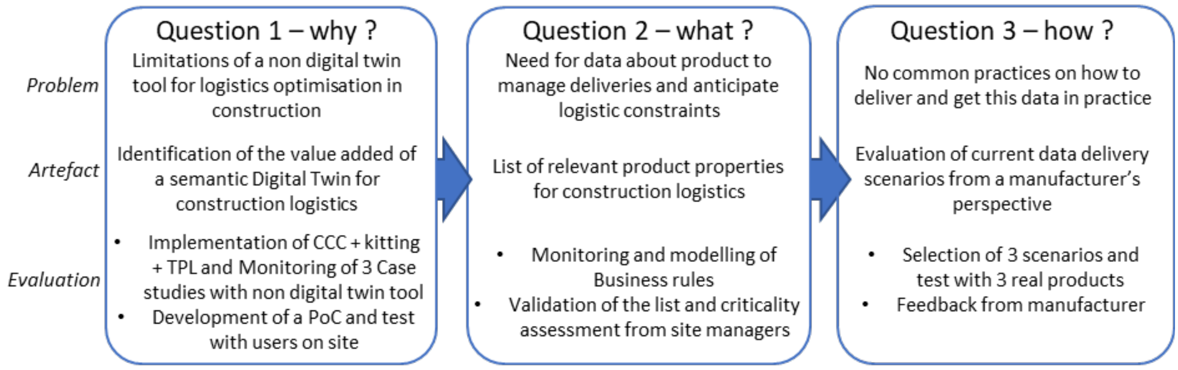

Figure 1: Research process with a Design Science Approach

As illustrated in figure 1, the questions were treated sequentially, and the DSA framework was applied for each question to deliver specific and replicable artefacts for the various stakeholders of the construction supply chain. Question 1 aimed to allow construction companies, logistician, and related practitioners to identify some expected value added of a PIM and Digital Twin tool towards Lean and Green logistics compared to a standard web platform. Therefore, innovative supply chain management methods were implemented by a General Contractor in Luxembourg (CLE- Compagnie Luxembourgeoise d’Entreprises) on 3 projects described in table 1. Previous publications about this project confirmed the strong potential for cost reduction and environmental impacts mitigation of a Lean Supply Chain Management while also emphasizing the key role of digitalisation (Berroir et al., 2021 and Maatar et al., 2022). The limitations faced by the teams with the web data platform used were collected through interviews. A PoC based on the digital twin concept (Boje et al., 2019) was designed to answer these limitations, and developed so that it could be tested on site with site managers (for predefined scenarios).

Question 2 aimed to provide to manufacturers, digital supply chain experts, standardisation bodies and researchers a set of product properties that are relevant for construction logistics based on the pilots. Therefore, logistic constraints on site (e.g., if an operator must unpack a package because it is too wide to cross a corridor) were collected during the monitoring of the pilots and modelled as a logical sequence, forming a so-called business rule. Accordingly, the product properties needed by these business rules could be listed, cross-checked with several existing classifications, and reviewed with sites participants for validation.

Lastly, based on this list of properties, question 3 aimed to provide practical feedbacks on data sharing and storing. 3 scenarios were identified and compared for 3 products from Knauf Insulation with the support of digital supply chain experts and BIM consultants.

CASE STUDIES DESCRIPTION

The 3 pilots involved overall 15 General Contractor's managers (from superintendent to director) from 2019 to 2023. More details on the projects are available in the following table:

Table 1: Description of the 3 case studies

Project	AUREA (in Differdange – LU)	OMNIA (in Esch-Belval – LU)	GRAVITY (in Differdange – LU)
Description	14 floor residential tower with 138 apartments	15 floor residential tower with 106 apartments	4 residential buildings (of 6 to 15 floors) with 205 apartments
Timeline	11/2019 to 07/2020	04/2021 to 05/2022	10/2021 to 03/2023
Trades involved	Tilling, floors, HVAC, bathtubs/showers, sanitary eq., joineries	Tilling, HVAC, bathtubs/showers, sanitary eq., plasterboards	
SCM/logistics innovations tested	Kitting, CCC, TPL	Kitting, CCC, TPL, multisite roundtrip with reverse logistics and some material picked up at close supplier	
Number of kits	1100	850	~1800 (ongoing)
Nb. of product types (references)	~900	~700	~300
Product choices	(Almost) fully flexible choices from the buyer		Choices from a shortlist
Digital tool and delivery management process	A Customized web data management platform on the software Airtable enabled to manage lists of kits and deliveries and to link it with files, photos, status, and planning on the cloud in real time. (See Maatar et al. 2022). It was used as a support for Last Planner System's meetings (Make-ready process).		

A benchmark conducted by the research team showed that most construction logistics software found on the market were focused on managing a delivery planning and on booking storage capacities or resources on site. This has little to do with enabling the detailed inventory of kits and the distributed management of deliveries between a logistic operator and the construction site(s). Thus, the general contractor designed and implemented its own web data platform for the pilots using the software Airtable. The detailed pros and cons of this precise software are not relevant for this study. The point is that, similarly to the other software found, it was representative of a "non-digital Twin" tool in the sense that it had no real-time (at least partly) automated data collection from the real world, no automated feedbacks to the real world, no simulation/problem solving capacity and no machine-readable product data integration.

RESULTS

EXPECTED VALUE ADDED OF A DIGITAL TWIN FOR LOGISTICS ON SITE (Q1)

As reported by Maatar et al. (2022), site managers were able to manage deliveries in kits with such a platform. Although preparing and maintaining the platform was time consuming, measurement showed that this outweighed the time that they usually lose in firefighting activities related to logistics.

However, in absence of machine-readable data, the web platform was not suitable for detailed product management inside kits and for multi-project and multi-criteria optimisation: the Omnia and Gravity sites were relatively close from each other (5km), but managers and logisticians couldn't plan complex roundtrips with the level of information they add and tended to schedule separate deliveries. Moreover, delivery times were often miscalculated because of unchecked delivery constraints (especially for products such as plasterboard). These limitations reported by site managers through interviews are summed up in the table 2. As proposed by Boje et al. (2019), a semantic Digital Twin may answer them. A PoC called TWISCO was designed to specifically illustrate how the DT concept can overcome these limitations. Tests on site (with tests data sets) confirmed the relevance of these features for site managers (fig. 3).

Table 2: Proposition of a Digital Twin application for Grean + Lean Construction logistics

Main limitations of web data platform used in pilot projects	**Features implemented in the TWISCO Proof of Concept (PIM + Digital Twin)**
Construction site's stakeholder and TPL operator need to know in detail what needs to be packed together, how and what are the characteristics of each package (e.g., weight)	A Kit management view allows to manage separate instances of products in each kit with their own properties and to manage and calculate the properties of the resulting kit.
Consistency between deliveries coming to the CCC and kit to be delivered need to be checked	Unique tracking of product instances in the kits using serialized GTIN (sGTIN) from GS1
Construction site's stakeholder and TPL need to assess when a kit should or not be delivered and what would be the impacts?	Planning integration + Space status management (may be automated with sensors) *Example: if there is humidity in the apartment delivery of wooden door should be postponed.*
As operators have a limited window of time to perform deliveries, delivery time need to be calculated considering constraints on site	Customizable constraint modelling through a "Business rules engine" *Example: a kit is too wide to cross a corridor, operator will lose time to unpack it and carry in separate batches*
TPL operator needs to be able to minimize both cost impacts and environmental impacts of complex multi-site roundtrips	Optimisation module with multicriteria optimization (using Genetic Algorithm)

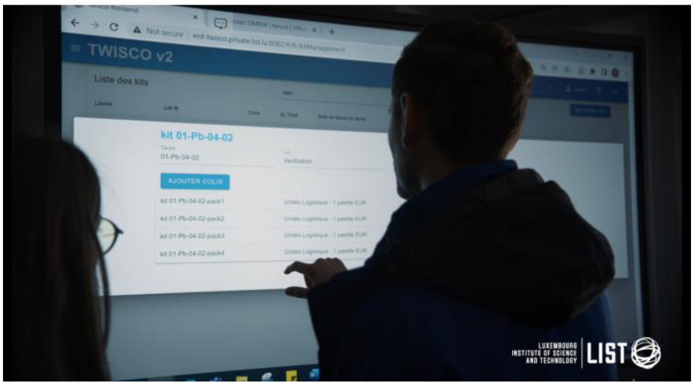

Figure 2: Testing on site of the TWISCO Proof of Concept

PRODUCT PROPERTIES FOR CONSTRUCTION LOGISTICS (Q2)

As a practical contribution to the 'Coordinating material deliveries on site' case for PIM stated by Peltokorpi and Seppänen (2022) and to enable tests with actual products, a list of the relevant 'standard data' for construction logistics was needed. The business rules, used to model the logistic constraints reported on the pilots, had product properties as a parameter, that could be extracted towards a first data model. With the support of experts from DSCIBE, it was crossed with existing standards such as ETIM and Peppol (OpenPeppol, 2017), which resulted in the list of properties hereafter. This list did not aim to be exhaustive nor definitive, but to contribute to the elicitation of key product data and to be representative of the type and amount of data needed to implement a semantic Digital Twin concept in practice. This list was submitted to the site managers to check the alignment with the characteristics they had to consider during pilots. Not all properties were of the same importance according to the feedbacks: While some characteristics such as weight or GTIN were mandatory to the concept proposed, other were situational. Accordingly, 'Must have' properties were highlighted by site managers, that encompass the most impacting problems faced. To help readability and future uses, the list was split in several sub cases ('purpose') and further explanations are proposed in description.

Table 3: Product Data for Construction Logistics: General data

Property	Purpose	Criticality	Description
Product identification (GTIN)	General	**Must have**	Global Trade Identification number 13-digit code
Seller Identification	General	Nice to have	GLN number of the company.
Manufacturer Identification	General	**Must have**	GLN or identification number
Key words (synonym)	General	Nice to have	Plain text
Product category	General	**Must have**	Categorization of the product type (e.g., windows). Should refer to existing categories in IFC, GPC or UNSPSC class.
Description	General	Nice to have	Plain text
Name	General	Nice to have	Plain text

Table 4: Product Data for Construction Logistics: Ordering, accounting, and kit definition

Property	Purpose	Criticality	Description
Ordering unit	Ordering, accounting, kit definition	**Must have**	Unit in which the order is expressed (square meters, linear meters, kg, pieces, …)
Minimum ordering quantity	Ordering/ accounting/ kit definition	Nice to have	If a threshold is defined for orders
Minimum package per pallet	Ordering/ accounting, kit definition	Nice to have	Minimum number of instances of the product type that can/must be stacked on one pallet (of the defined pallet type)
Maximum package per pallet	Ordering, accounting, kit definition	**Must have**	Maximum number of instances of the product type that can be stacked on 1 pallet.

Table 5: Product Data for Construction Logistics: Handling and transport

Property	Purpose	Criticality	Description
Gross product weight	Handling, transport	**Must have**	Value in kg. May include packaging
Net product weight	Handling, transport	Nice to have	Value in kg without packaging (useful only if packaging is a big part of the weight)
Pack quantity	Handling, transport	Nice to have	The number of packed units that are in the orderable unit. E.g., if the orderable unit is a pallet that contains 30 boxes then the packed units are BOX and the packed quantity is 30.
Roll diameter	Handling, transport	Nice to have	Specific to cylinder products
Product density	Handling, transport	Nice to have	Only useful to determine weight if not given.
Product volume	Handling, transport	Nice to have	Relevant for truck optimisation with stackable products
Product length (packaged)	Handling, transport	**Must have**	Deep dimension of the packaged product
Product width (packaged)	Handling, transport	**Must have**	Latitudinal dimension of the packaged product
Product height	Handling, transport	Nice to have	Needed when products can be stacked or to check if product can go through some doors/lifts
Numeric pack size	Handling, transport	Nice to have	Consumable unit quantity Specifies the number of consumable units that are in each orderable unit. E.g., if the orderable unit is a pallet that contains 30 boxes, then the packed units are box and the packed quantity is 30 and the numeric pack size 30*orderable unit
Type of handling unit	Handling, transport	**Must have**	Type of pallet used (pallet EUR, destructible pallets, no container, other (e.g. backrest pallets)
Handling instructions	Handling, transport	**Must have**	Plain text: comments of the manufacturer on how to use / or manipulate the material
Is it fragile	Handling, transport	**Must have**	Boolean, high risk of breaking

Table 6: Product Data for Construction Logistics: Installation

Property	Purpose	Criticality	Description
Vapour permeability	Installation	Nice to have	If available, can be used to determine the sensitivity to humidity. Potentially useful for further Use cases other than logistics
Thermal resistance	Installation	Not relevant for logistics	R-value, if necessary, a use or storage temperature should rather be given
Use temperature	Installation	Nice to have	Range of acceptable temperature for using the product as intended
Storage temperature	Installation	Nice to have	Range of acceptable temperature for storage

Table 7: Product Data for Construction Logistics: Installation

Property	Purpose	Criticality	Description
Maximum storage humidity	storage	**Must have**	Maximum humidity conditions before risk of degradation / property losses for the product
Maximum storage temperature	storage	**Must have**	Maximum temperature conditions before risk of degradation / property losses
Minimum storage temperature	storage	**Must have**	Minimum humidity conditions before risk of degradation / property losses for the product.
Sensibility to sun light	storage	Nice to have	Some material might be for example discoloured if they are left exposed to the sun

Table 8: Product Data for Construction Logistics: Reverse, Waste management

Property	Purpose	Criticality	Description
Packaging plastic sheet	Reverse, waste management	Nice to have	Amount of plastic with usual packaging. Can be useful for reverse logistics
Packaging wooden pallets	Reverse, waste management	Nice to have	Amount and type of wooden pallet with usual packaging. Can be useful for reverse logistics

PRODUCT DATA DELIVERY FROM THE MANUFACTURER (Q3)

In the 3 pilot sites, only the "must have" properties of the products managed would represent more than 20 000 values. For a construction company, filling and maintaining such a database is unrealistic and cost-ineffective, even if data would come in a machine-readable format. Particularly in these cases where product choices validated by the buyer at a very late stage of the project. This responsibility falls then on manufacturers, but from a supplier's perspective, knowing how to provide the data requires tackling practical questions 1° and 2° below, that were tested for 3 products from Knauf Insulation (e.g., https://knauf.be/fr/produit/acoustifit).

1° Where to store data so that it can be managed in time, at minimal cost?

The purpose of these experiments was not to find the best solution on the market from an economical or technical perspective, but to compare several approaches different by nature from a supply chain perspective. Accordingly, three patterns were identified and tested: data can be stored in common data bases/databanks (1), data can be stored in the BIM objects (2), or data can be piggybacked to e-procurement messages (3).

Using a common product data bank (GDSN)

An approach based on National databases is emerging in many countries especially regarding standardized Life Cycle Assessment Data (e.g., https://www.oekobaudat.de/). For the tests, a product data base called "GDSN" (which was originally designed and used for food) was used.

Pros: - Minimal needs in terms of software or pre-existing data (apart from a GTIN) from both sender and receivers' point of view

- Consistency with GS1 regulations (for the case of GDSN)

Cons: - The system was closed, meaning that adding properties or bypassing asked fields was not possible. This might not be the case for all solutions of type "databank"/common database, but the flexibility of the system raises questions in front of unanticipated data need or changes in the standards raises questions.

Integrating all (the required) properties in the BIM file

Alternatively, several big manufacturers provide access to BIM libraries where an IFC file (or other BIM formats) can be downloaded for each product (e.g., bimlibrary[5] from Saint-Gobain). In some cases, it is even possible to generate BIM file for a system of several products assembled including products of other manufacturers as for example in Knauf Insulation (2022).

Pros: - All information is standardized.

- Fully customizable within available properties at manufacturers level. Example: https://test.hybrid.pl/knauf_insulation/bim/bim_generator/form.php?id=7977
- Considered as more convenient from a (big) manufacturer's perspective

Cons: - May be less effective procurement-wise
- Requires having BIM libraries of the products
- May restrict the access to data for software outside of BIM environment

Sending data (and some potential meta data) as a message for e-procurement (Peppol)

Peppol allows a network of eProcurement partners to be connected and exchange standard-based documents (OpenPeppol, 2017). Thus .xml files can automatically be sent by any internal system and 'translated' at the receiver's level with customizable integrators.

Pros: - Considered as more convenient from a procurement and multi-level supply chain, - Natively supports logistics workflow

- Data to deliver is easily customizable, and can be aligned with Data Templates

Cons: - At receiving end, using Peppol may entail to maintain multiple copies of the same product data instead of maintaining a single catalogue of product types

- Harder to implement on manufacturers side (new system of data sharing)

2° How to structure data in sync with existing classifications to ensure interoperability?

In all three scenarios above, the key to identify a property is its Uniform Resource Identifier (URI), identified thanks to data templates through the bsDD. Every property in the list (Tables 3 to 8) were looked after in the bsDD, in some of the main product data classifications available (ETIM, eClass) and in the Peppol standards as shown in table 9.

Table 9: Identification of targeted data in current classification

	number of properties	bSDD	ETIM	eClass	Peppol
All properties	34	71%	42%	32%	84%
Only "Must have"	14	73%	45%	36%	100%

The percentages in table 9 indicate that as new use cases or applications are developed, a significant amount of the properties might be out of available classifications. More importantly, these properties were spread in several classifications, which made their identification tedious and thus, limited replicability and efficiency from a manufacturer's perspective.

DISCUSSION

Construction Logistics and Digital Twin on site

Although TWISCO was usable for tests and demonstrations, it is still a PoC with a TRL5 (Sadin 1988). As such it is not fully functional, and the value added of the Digital Twin Concept proposed in table 2 needs to be confirmed and potentially extended with its full implementation

[5] https://bimlibrary.saint-gobain.com/

in real conditions. TWISCO's business rules engine could be used as a framework for bottom-up identification of logistic constraints through new case studies. These should also consider the potential limitations of Digital Twins in construction regarding the human related aspects highlighted by Noueihed and Hamzeh (2022). Sensor's implementation on construction sites and automated tracking from the supplier proposed by the TWISCO PoC should also be more studied. Indeed, these technologies may contribute to the Last Planner System by enabling a more trusted Make Ready Process. Moreover, the environmental impact mitigation from a multi-site delivery optimisation algorithm should be demonstrated in practice as well.

Predefined Group of properties in the Product Data Templates for specific use case

Product data templates are defined by product type. Based on current work, authors call for more generic predefined group of properties based on use cases such as "logistics". This paper is a contribution towards such a standardized set of property for construction logistics. Authors emphasize that such a group of properties should not be restricted to the "handling or transport properties" as other aspects were identified as necessary to optimize logistics based on Just-in-time principles (for example installation aspects). This list is however preliminary and limited in scope. More project types, product types, and logistics scenarios (e.g., multi modal logistics optimization, reverse logistics, logistics for reused materials) need to be investigated. Other similar applications such as the circular economy with the 'Product Circularity Data Sheet' (Mulhall et al., 2022) may benefit from such a standardization effort.

Manufacturer's perspective on PIM

To encourage manufacturers to openly give access to their data, there is a need to either set regulatory obligations or clarify the business model and competitive advantage. Therefore, understanding and awareness should be raised in the industry. From the manufacturer's perspective, this might require simplifying and clarifying the concepts used (standards, data formats, data templates, data sheet, data sets, classifications, norms, data dictionary, properties, attribute, etc…). Moreover, this study indicates that there might not be a "silver bullet" solution, but different options depending on the type of products, experience with BIM and PIM, the number of reference or ERP system used, etc. This should be elaborated in further studies.

CONCLUSIONS

This paper investigated how data continuity may be achieved in construction and how it could support data driven logistics aiming at reduced environmental impacts and costs. Based on operational feedbacks from 3 projects with almost 4000 kits delivered from a CCC, limitations of a classical web data platform were identified and a proof of concept of semantic Digital Twin was proposed to answer them. This PoC enables to manage 'instance data' of products (e.g., unique reference of material within a delivery) which facilitates kit management. It can be subsequently linked with 'process data' (e.g., delivery status) which are essential to manage the process in the sense of Lean Construction and to integrate 'standard data' which encompasses physical characteristics of a type of product (e.g., weight). What standard data should be exchanged and how it can be practically delivered was studied with real products from both ends of the supply chain. Accordingly, this research contributes to Lean Construction by identifying some potential benefits and perspectives of Digital Twin and PIM for SCM. It contributes to the fields PIM, BIM, and Digital Twin by presenting use case of these technologies with concrete implication in the execution phase, by comparing several patterns for delivering the data and by reporting a limit in current definition of Product Data Templates. Thus, authors advocate for predefined sets of properties for specific use cases such as logistics or circularity in the Data Templates (that could be built upon the list proposed in this article) and highlight the need to raise awareness amongst the industry through more practical cases.

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STRATEGIC PARTNERING BETWEEN CLIENT, CONTRACTOR, AND SUBCONTRACTOR

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ABSTRACT

The concept of strategic partnering has recently gained significant attention in the Norwegian construction industry. Strategic partnering is a project delivery method that emphasizes a more collaborative approach than traditional delivery methods. It shares similarities with a Lean project delivery approach, as both seek to optimize and create more collaborative projects. In this paper, strategic partnering is broken down into three key elements of Lean Construction: contractual, organizational, and relational elements. Through this, the paper aims to contribute to understanding strategic partnering between a client, general contractor, and a key subcontractor by addressing the following research questions: 1) How is strategic partnering practiced in Norwegian construction projects, and 2) What are the experiences of practicing strategic partnering in Norway?

An in-depth case study was conducted to investigate ways to enhance strategic partnering in future projects. A combination of a literature review and semi-structured interviews were used for data collection for this paper. The findings show that using strategic partnering improved project outcomes, with trust, early contractor involvement, contingency of key participants, and problem resolution being crucial aspects of the collaboration. However, more attention should be paid to evaluating the other parties in the context of the strategic partnership.

KEYWORDS

Strategic partnering, strategic alliancing, project delivery models, Lean construction, collaboration.

INTRODUCTION

As building projects become increasingly complex, alternative project delivery methods are becoming more prevalent in the construction industry (Engebø et al., 2020). The new delivery methods seek more integration in the construction process by involving key parties in the early stages and forming an integrated project team. A core driver for this change can also be found in the lean community through the emergence of lean project delivery with its emphasis on establishing a collaborative project organization, relational contract, and lean operational system to align and integrate key participants and encourage a collaborative environment (Mesa et al., 2019).

Nevertheless, there is a need for further research in the area of collaborative project delivery. Partnering is one such method, which can take the form of a strategy or a practice of different

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versions. According to Lahdenperä (2012) partnering can also be viewed as a philosophy. Bennett and Jayes (1995) define partnering as a management approach in which two or more organizations utilize each other's resources to attain specific goals. This form of collaboration is particularly useful in complex projects with a high degree of uncertainty and a need for collaboration among the parties (Eriksson, 2010).

In the literature, there are commonly two forms of partnering that occur: project and strategic partnering (Beach et al., 2005). Project partnering is limited to a specific project and aims for short-term effects (Bygballe et al., 2010). On the other hand, strategic partnering can span over several years and projects, and seek long-term gains (Beach et al., 2005; Cheng et al., 2004). Both forms are relatively less prevalent in project-based industries compared to production-based industries where they have existed for a longer period (Bygballe et al., 2010).

Strategic partnering can be a way to implement Lean principles as the collaboration lasts for a prolonged period and the relationships between the parties are strengthened through collaboration. In other industries, there has been found that strategic partnering has a positive effect on lean strategies, lean manufacturing, and lean design (see for example, Jayaram et al., 2008). In other words, the concept should be transferable to the construction industry in line with the lean philosophy's approach to continuous improvement, efficiency, and value creation.

Sundquist et al. (2018) and Zheng et al. (2020) emphasize the need for further research to comprehend the concept of strategic partnering. Additionally, case studies on strategic partnering are necessary, as the previous research has primarily consisted of cross-sectional studies (Zheng et al., 2020). According to Bygballe et al. (2010), there is little documented research regarding strategic partnering between multiple actors. There is also a knowledge gap in the literature about the experiences and effects of strategic partnering, especially in the Norwegian construction industry. However, this does not imply that strategic partnering is not practiced in the construction industry. It is therefore of interest to gather and collect experiences from parties who practice strategic partnering in their projects. Lately, there has been a study about strategic partnering between a contractor and a designer in Norway (see Paulsen et al., 2022).

The purpose of this paper is to identify the success factors of strategic partnering in Norwegian construction projects. Additionally, it will investigate the experiences of partnering across multiple projects. It will be based on relevant literature and two case projects. The following research questions (RQ) have been developed for this in-depth study:

- RQ1: How is strategic partnering practiced in Norwegian construction projects?
- RQ2: What are the experiences of practicing strategic partnering in Norway?

This study examines two building projects that utilize a Design-build contract that features predefined criteria for collaboration. The main focus of this research is on the relationship among the client, the contractor, and the subcontractor, as the same partnership is tracked throughout the entirety of the first project and the early stages of the second. The general contractor was engaged in the design phase together with the client and the electrical subcontractor was engaged before commencing construction.

THEORETICAL FRAMEWORK

Strategic alliances have a central place in the lean philosophy. For Toyota, partnering in the supply chain was one of the four core processes. Garnett et al. (1998) believe that a premise for a lean construction process is that alliances, operationalized through the project team, work on a series of projects, continually developing the product, applying quality improvement and waste reduction techniques, and incorporating arrangements for learning and continuous improvement.

COLLABORATIVE PROJECT DELIVERY METHOD

Miller et al. (2000) describe a project delivery method as «a system for organizing and financing design, construction, operations, and maintenance activities that facilitates the delivery of a good or service». According to Klakegg (2017), some will argue that adapting the project delivery model to the specific project will be most appropriate. Others will argue that a standardized project delivery model will contribute to less misunderstanding and disagreements from project to project. To handle projects with higher risk, uncertainty, and complexity collaborative project deliveries can be a preferred option (Tadayon, 2018).

There is a distinction between hard and soft elements in collaborative project delivery (Wøien et al., 2016). The hard elements can be found in the contract, while soft elements are the outcome of using process-oriented methods during the project. The findings by Engebø et al. (2019) conclude that the most important soft elements were top management support, openness/transparency, trust, shared goals and motivation, and attaining the right people. Whether the client's management can provide continuous support lies on the client's resources and is considered a critical success factor.

STRATEGIC PARTNERING IN THE CONSTRUCTION INDUSTRY

The literature review indicates a clear distinction between project partnering and strategic partnering (Beach et al., 2005; Bygballe et al., 2010). Project partnering is a method that is specific to a particular project, focuses on short-term effects, and is more results-oriented (Beach et al., 2005). On the other hand, strategic partnering is geared towards achieving long-term effects of collaboration between various parties. This delivery method lasts for multiple years and projects and is more process-oriented than project partnering. Establishing trust, shared objectives, and commitment among project members are important factors for a long-term relationship between involved parties (Bygballe et al., 2010). According to Koolwijk (2018), strategic partnering is a delivery method in which the owner, contractor, and key subcontractors enter a long-term partnership. Additionally, contractors and subcontractors are allowed to work on follow-up projects if they meet predefined criteria set by the owner. Characteristics of strategic partnering include open-book accounting, shared risk and reward, and open communication. According to Zheng et al. (2020), transitioning from project partnering to strategic partnering poses a substantial challenge with a focus on the institutional environment, organizational structure, and team dynamics. Furthermore, previous research suggests that a more strategic approach to project partnering can enhance projects in the construction industry (Moller & Bejder, 2004).

There have been successful examples of strategic partnering, but these are mainly restricted to client-contractor (Shimizu & Cardoso, 2002). However, there is a need to explore the phenomena all through the supply chain. To increase productivity in projects, contractors should improve their relationship with subcontractors and provide feedback and evaluations (Eom et al., 2008). A case study by Beach et al. (2005) found that the majority of interviewees from the general contractor believed that a long-term partnership with subcontractors would provide better support throughout the project. It is also emphasized that the benefits of collaboration will be apparent after several years of collaboration between the parties. The key to success in collaboration is the development of a shared understanding of expectations, shared visions, and a common goal for the project. A case study by Crutcher et al. (2001) found that the strategic partnership between an electrical subcontractor and supplier led to increased productivity and efficiency in material handling. A long-term partnership, based on principles that benefit both parties, will most likely be beneficial for all parties involved in the execution.

A LEAN PERSPECTIVE ON STRATEGIC PARTNERING

Oakland and Marosszeky (2017, p.21) propose that for lean construction to be successful, project delivery should emphasize the creation of an integrated organization with the commercial interests of the parties aligned around the efficiency of the project as a whole. A lot of attention in lean management has been aimed at collaboration and partnering between different parties to enhance value creation (Jylhä & Junnila, 2014). Research has shown that combining Lean principles and partnering can create positive synergies (Falch et al., 2020). According to Karanjawala and Baretto (2018), the implementation of Lean Construction in partnering has resulted in more open communication, trust and transparency, and identification of constraints and non-value adding activities. The concept of strategic partnering corresponds with the Lean philosophy of continuous improvement as it aims to achieve learning outcomes both at the organizational level and across different projects (Paulsen et al., 2022). Furthermore, since strategic partnering is lasting for more years and over several projects, it can be easier to implement Lean principles in the involved organizations.

THE KNOWLEDGE GAP

Most of the literature regarding strategic partnering has been limited to either client-contractor, contractor-subcontractor, and a few contractor-designer. However, few publications examine strategic partnering with multiple actors, such as client-contractor-subcontractor, and this aligns with the findings by Bygballe et al. (2010). In general, both Sundquist et al. (2018) and Zheng et al. (2020) state that it is a research gap regarding the concept of strategic partnering and that more case studies should be conducted.

METHODOLOGY

This study employed a qualitative research design by combining both a literature study and a case study. The literature study was based on the prescriptions of Arksey and O'Malley (2005) and the case study was designed based on the methods outlined by Yin (2018) for single-case studies. The goal of this research was to examine the phenomenon of strategic partnering between a client, contractor, and subcontractor in the construction industry in Norway.

The literature study was conducted to provide a comprehensive overview of the existing knowledge on strategic partnering in the construction industry. A structured search of relevant literature was conducted using various databases such as Scopus, Web of Science, IGLC, and Oria. After the literature search was reduced to a manageable amount the sources were evaluated by predefined criteria. The sources were evaluated by criteria such as the title, relevant keywords, abstract, conclusion, and an overall assessment of the publication. If the publication met the criteria mentioned above, reliability and credibility were considered.

The case study was conducted to provide in-depth insights into the phenomenon of strategic partnering in the construction industry in Norway. The case chosen for this study was two building projects within the same geographical region, and the same organizations participated in both projects. Table 1 shows some information about the two projects which were analyzed. Having been established for some time, it was possible to gather more detailed and nuanced information about the strategic partnership through different parties.

The primary method for data collection applied in the case study was in-depth semi-structural interviews. The selection of participants for the study was based on their roles in the projects. A total of ten informants from the client, general contractor, and main subcontractor were selected from the case projects. All ten interviewees participated in the first project while seven of these were also participating in the second project. The semi-structured interviews were conducted digitally. A list of open-ended questions was used as a guide for the interviews within the following main categories: contract, organization, and relations. The interview questions were tailored to the research questions and for each subcategory, the participants were asked about their actions, experiences, and suggestions for what could have been done differently. The interviewer was also able to follow up on any additional points that arose during the interview. All interviews were recorded and transcribed for analysis. An example of an interview question was: “How would you describe the level of trust in the projects?”.

Table 1: Facts about the two case projects.

	Project A	**Project B**
Location	Oslo, Norway	Oslo, Norway
Building type	Rehabilitation and new-built school building	New-built office-building
Contract type	Design-build with collaboration	Design-build with collaboration
Building dimension	ca. 17.000 m^2	ca. 24.000 m^2
Start of construction	Q2 2019	Q2 2022
Takeover	Q2 2021	Q2 2024
Sustainable goal	BREEAM[1] Excellent	BREEAM[1] Excellent

[1]BREEAM stands for Building Research Establishment Environmental Assessment Methodology.

The data collected from the literature study and the case study were first analyzed separately, but afterwards they were analyzed against each other. The literature study data were analyzed using thematic analysis. The data collected from the case study was analyzed using a process of coding according to contractual-, organizational-, and relational elements.

FINDINGS AND DISCUSSION

This chapter presents findings from interviews in the case study and evaluates them using the case study and theoretical framework. The chapter is structured into sections on contract, organization, and relations.

CONTRACTUAL ELEMENTS

The contract plays a vital role in any construction project. Even if the partnering concept emphasizes collaboration and building a relationship beyond the formal contract, there must nevertheless be a contractual relationship that ensures the foundation of the strategic partnership. In the case projects, the most important contractual relationships were between the general contractor and the client, and between the general contractor and the electrical subcontractor. In the early stages of the first project, the client made a strategic decision to procure a contractor who had the capacity and competence to partake and collaboratively develop the project together with the client. Key contractual elements identified were the following:

Design-build with collaboration was the preferred contract between the client and contractor.

Procurement not just on lowest price: Several different criteria were used. The competence of the contractor’s personnel was a vital factor in collaborative project delivery.

Incentive model: where both client and general contractor worked towards a target price.

The parties did not prepare a formal agreement in advance that established that the partnership should continue through all the projects. The lack of an up-front strategic alliancing agreement seems to be in line with previous research (see for example Paulsen et al., 2022). An explanation may lie in the nature of projects. In contrast to industrial production, where the alliance will continue to produce the same product repeatedly, the parties will produce unique products repeatedly. For the parties, it would therefore be too great a risk and uncertainty associated with formalizing the strategic collaboration at such an early stage (i.e., before the first project). Instead, they seek to use the first project to build a relationship and see if they can achieve some partnering effects that can form the basis for further collaboration.

The importance of selecting people who can collaborate and see both sides of an issue is emphasized, and it puts high demands on project management. In sum, the client allocated a lot of resources to the contracting process as their objective was to establish a strategic partnership with the contractor if the collaboration in the first project succeeded. As a supplement to price, experience, competence, and references were considered important criteria for selection, especially for complex rehabilitation projects. For the selection of an electrical subcontractor, the main criteria are based on price. However, it is pointed out by the subcontractor that the relationship and experience from previous collaboration could have influenced the choice of the electrical subcontractor.

In both projects, an incentive model was used where both client and general contractor were involved with a target cost contract, as described in Zimina et al. (2012). If the final cost was below the target price, the profit was shared between the parties. This also applies to overruns up to a certain amount. If the costs exceeded a certain percentage of the target price, the contractor had the risk. The contractor was awarded if they made good purchases that didn't affect the required quality. Furthermore, the design and target price were developed in parallel in this project. This allows the client to make more optimized decisions, increases and extends project flexibility, and reduces and shares risks between the parties. On the other side, late changes in the project can lead to more stress and friction in the design group managed by the general contractor. There was no further incentive in the contract, but based on the performance of the first project there was no doubt that the contractor would get the second project. For the subcontractor, there were not used any contract nor cost-related incentives.

According to the interviewees, there were some formulations in the contract regarding how the collaboration through the project should be. However, all interviewees state that it can be difficult to appraise if formulations, such as trust, comply with the contract during the project. To make strategic partnering work every party must put in the effort and integrate themselves within the project organization. The issue of productivity within the construction industry has been a longstanding concern, and therefore this was addressed in the interviews. The first project was delivered ahead of schedule, with a finished product that met the client's expectations and demands, with a few minor discrepancies. Additionally, the project was completed within the target price agreed upon by the client and contractor. Given the complexity and short implementation period of the project, the subcontractor deemed the overall productivity to be high. This corresponds with the findings of Kubal (1996) where strategic partnering between the client, contractor, and subcontractor improved the project results.

ORGANIZATIONAL ELEMENTS

In both projects, it was important for the client with early contractor involvement. The contractor was involved in the predesign phase in both projects. The first project was priced based on the completed pre-project, typically at the frame application level. The electrical subcontractor was involved early after the general contractor was chosen, as a part of the contractor team. The interviewees presented a nuanced view of the early involvement of the contractor as they listed both advantages and disadvantages. In the early phase of the project, it can be difficult for the client to assume or foresee how much different operations will cost during the project and how long it will take to complete each operation. With early involvement, the contractor will be able to contribute with knowledge of the constructability (Tadayon, 2018).

Early involvement of key parties can also lead to increased trust between the key parties over time and improve efficiency. The involvement of subcontractors before the commencement of construction allows for better preparation and increased preparedness for the project (Nevstad et al., 2018). As Beach et al. (2005) describe, the subcontractor will be able to provide better support if they are involved at an early stage. However, both the general contractor and the electrical subcontractor state that too early involvement of contractors can lead to higher uncertainty and more confusing surroundings. There should be some goals and objectives developed by the client before contractors get involved. For example, the tenant joined the project late, with the result that significant changes to the design were required. If the involvement of different parties isn't strategically assessed in advance, it could result in wasteful activities such as rework on the design of the project. Reflecting on the first project, it may have been beneficial for the tenant to have been involved earlier, or the design team could have made their solutions more flexible. If the solutions are being locked at an early stage, it could lead to waste because changes require redesign.

During the first project and the current early phase of the second, there were very few conflicts among the parties involved. There was a clear strategy and mutual understanding among the different parties that issues or disagreements should be addressed at an early stage and a project level. One of the reasons for this approach was to prevent the history of the conflict from being forgotten in case it was prolonged. This can be said to be in line with the partnering philosophy as one seeks to overcome disagreements or conflicts not by contractual clauses but by their shared commitment and interest in the project. One interviewee stated: "There were no conflict or bigger disagreements between the client and the contractor throughout the projects". However, another interviewee stated: "Between the contractor and the subcontractor, there may be a few more disagreements". This is because the execution phase is more dynamic than the early phase, and multiple disciplines needs to be coordinated.

If a resolution could not be reached between the client and the tenant, it was then brought to a steering group composed of representatives from the client's organization and the tenant's organization. If they were unable to reach an agreement, the matter was escalated to a dispute or legal action. The client evaluated both the progress and the economic impact of the case before making a final decision. According to the interviewees, there were minimal conflicts and no unresolved cases. There is a mutual understanding among the interviewees that disagreements primarily occur during the construction phase, whereas the pre-project phase is relatively static.

In the transition from the first project to the second, considerations were made regarding the transfer of key personnel. One interviewee stated: "The most important element is to transfer key personnel from the previous project". Continuity among key project participants is an important factor for achieving success in a long-term partnership (Black et al., 2000). The general contractor plans to transfer four out of eight individuals from the project team, while the electrical subcontractor transferred all their personnel from the first project to the second. This continuity can create synergies for the upcoming project as the trust and relationships between the participants have already been established through the previous project. This aligns with the findings of Sundquist et al. (2018), where relationships developed through project partnering can be extended into strategic partnering. According to an interviewee, the upcoming project may be vulnerable if the key participants are not transferred. The level of uncertainty is reduced by the parties becoming familiar with one another and having a clearer understanding of each other's methods and performance capabilities. This corresponds well with the findings of Bresnen and Marshall (2002), where a lack of continuity of key personnel and relationships can lead to problems for the long-term collaboration and transfer of knowledge between the parties.

Table 2 presents experiences within organizational elements. An interviewee noted that productivity was deemed satisfactory in the project due to two key factors. Firstly, swift decision-making by the client, contractor, and tenant regarding any possible changes to the building helped maintain an optimal workflow in the project. The strong trust and relationship established among the parties facilitated an efficient decision-making process. Secondly, the project's progress plan was well-conceived, resulting in minimal delays caused by the need to wait for other contractors to complete their work.

Table 2: Summary of experiences within organizational elements.

Element	Good experiences	Bad experiences
Early contractor involvement	Enables better preparation and increased understanding of the project; enhances trust between the parties; increases efficiency	Too early involvement may lead to more confusion and uncertainty; can lead to more waste if solutions are locked in too early.
Conflict resolution strategy	Having a clear strategy and mutual understanding, disagreements or issues can be addressed at an early stage	If a resolution can't be reached, disputes can escalate to legal action
Continuity of Key Personnel	Can reduce uncertainty and create synergies; companies become familiar with each other's working methods and capabilities.	If there is a lack of continuity of key personnel, long-term collaboration and knowledge transfer can be more difficult

RELATIONAL ELEMENTS

Throughout the first project and early phase of the second, all interviewees reported that the level of trust between the parties was sufficient and increasing. By understanding each other's working methods mutual trust developed throughout the projects. In a rehabilitation project, such as the first one, uncertainty can be a challenging factor and difficult to control. According to all interviewees, trust is a prerequisite for collaborative project delivery and a successful strategic partnership. As one interviewee stated: "Trust is essential in this collaborative model. Without it, such contracts do not function properly". According to another interviewee, it typically takes around one year to establish a trustworthy relationship. Trust between the parties is crucial during chaotic periods. As Chan et al. (2003) describe, uncertainty can be an underlying challenge in building trust between parties. This is also acknowledged by the interviewees. However, due to the early involvement of both the contractor and subcontractor they were able to start building trust and relationships between the project participants at an early stage. Koolwijk et al. (2021) state that trust is one of the success factors for strategic partnering. It is noteworthy that trust naturally develops when the project results are positive (Beach et al., 2005). However, incidents that threaten the trust between the project participants on a larger scale than in the first project can occur. As this was a complex and large-scale building project, late changes from the tenant could have been challenging for the trust between the parties.

Throughout the projects, there have not been implemented dedicated evaluation meetings regarding the partnerships. However, there has been some evaluation ongoing through the general contractor reporting on quality, economics, and progress. The feedback the contractor receives from the client will indicate the client's satisfaction. A similar report is done by the subcontractor at the same time. The interviewees state that it is common to conduct an internal evaluation of the projects. However, according to an interviewee, it is not common to conduct other forms of project evaluations during or after projects. There is mutual consent among the interviewees that evaluation meetings are something they should establish between the parties, especially at the end of projects. Often it can be challenging to change the scope and take a step back when you are in the project. One should ask what went well and what could have been done better. Since the pre-project for the second project was underway while the first project was in the final phase, the client did not want to disturb the contractor with heavier evaluations. Such a period can be very hectic for the contractor, but the client still believes it could have been done at a later time. Given the lack of formal agreements for the strategic partnership between the parties, the continuity of key participants and transfer of experiences was important.

This kind of knowledge transfer could have contributed to fewer mistakes in future projects. According to the findings of Cheng et al. (2004), conducting evaluations of internal performance within the organization is important for achieving success with strategic partnering. This aligns with the execution of the first project, where internal evaluations were carried out by all three involved parties. However, the general contractor should have conducted a more comprehensive evaluation of the electrical subcontractor to create a win-win relationship in the long term (Eom et al., 2008). Given that the subcontractor has worked with the general contractor previously, it could be beneficial to conduct evaluations to further develop the partnership and at the same time identify opportunities for improvement. One interviewee explains that collaboration combined with predictability is essential for delivering good results. Key relational elements were identified:

- The level of trust between the involved parties was sufficient and increasing throughout the first project and through the start of the second.
- Trust is a prerequisite to successful strategic partnering and collaborative project deliveries.
- Evaluation of the project and collaboration should have been carried out, especially at the end of the projects.

A successful strategic partnering relies, among other things, on effective collaboration between the contractor and subcontractor. Research indicates that by developing a positive relationship between them, productivity can also be enhanced (Eom et al., 2008). Additionally, the electrical subcontractor plans to use the same supplier on the second project and this could lead to more productivity according to Crutcher et al. (2001). However, it can be quite challenging to quantify whether productivity was good as there is little comparison basis.

CONCLUSIONS

This study analyzed two case projects to identify the presence of contractual, organizational, and relational elements in strategic partnering. Furthermore, it contributes to research on Lean construction by exploring strategic partnering as a collaborative project delivery method. The examination included an examination of the client, general contractor, and electrical subcontractor. This study provides a detailed and in-depth examination of strategic partnering, and as such, the results should not be considered representative of the broader phenomenon. Rather, the findings may offer a more in-depth understanding of the topic and be of use to individuals and organizations who consider strategic partnering in their projects. Furthermore, this research may also contribute to the existing knowledge about strategic partnering. The study reveals that many principles and characteristics outlined in the existing literature regarding strategic partnering were also present in the case projects. It was found that spending excessive time formulating collaboration specifications is an unnecessary and non-value creating activity. Project participants in the first project experienced improved productivity, aligning with the Lean philosophy of creating value for the client. The essential part of the collaboration between the parties is that each participant commits and dedicates themselves to the partnership.

The client and contractor developed a target price to ensure shared risk and reward, which can be important in collaborative project deliveries. Additionally, this study found that early contractor and subcontractor involvement is an important success factor in strategic partnering. It contributes to both establishing a relationship between the parties and building trust at an early stage. At the same time, the contractors are more prepared to commence the execution phase. Furthermore, a clear hierarchy for conflict resolution is emphasized through strategic partnering. There was a clear understanding between all project participants that any conflict or disagreements should be resolved at the project level. Continuity among key personnel in all parties throughout the projects was an important factor because replacing one of the main participants would require building new relationships from scratch. The following critical success factors were identified throughout the projects in a non-specific order.

- Target price development
- Early contractor involvement
- Building relationships at an early stage
- Conflict resolution strategy
- Contingency of key project participants
- Evaluation between projects

So far, the case study reveals that there is currently a lack of established best practices for evaluating each other's performance within the strategic partnership. To ensure the implementation of Lean principles, such as continuous improvement, it can be beneficial to arrange meetings where collaboration between the parties is evaluated. This can provide useful information about potential changes for both the pending and upcoming projects throughout the whole supply chain. To create a deeper understanding of the effects and benefits of strategic partnering in the construction industry further research is needed, including case studies and interdisciplinary studies.

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SLACK: WHAT IS LACKING ON SUPPLY CHAIN RESILIENCE STRATEGIES?

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ABSTRACT

In complex systems, supply chains are more exposed to variability and uncertainties that lead companies to suffer negative effects on their performance and may even collapse. The civil construction sector is seen as a complex socio-technical system, therefore it must consider strategies that deal with these disturbances. Slack and resilience in the supply chain are topics that have already been discussed in several sectors of the industry and deal with these variables, however the literature is recent for the civil construction sector. It is understood that Slack can provide an improvement in the effect of supply chain resilience, however, there is no theoretical discussion that points out similarities and complementarities between slack and the concept of resilience in the supply chain to shed light on the uses and limitations of the practices. The study in question makes a theoretical discussion based on a literature review about these systems, compares their practices and strategies, similarities and complementarities and finally proposes future research. Findings of this study shows that one of the strategies like flexibility is more advanced on strategic issues such as pricing and flexible contracts in supply chain resilience theory than on slack theory. Other contributions are discussed for collaboration, social capital, margin of manoeuvre, agility and redundancy strategies.

KEYWORDS

Supply chain resilience, slack, strategies.

INTRODUCTION

Disruption in the supply chain is a phenomenon related to the interruption of the supply flow due to an unexpected event, usually having a high negative impact on the performance of organizations (Azadegan et al., 2021). Costs, revenues and deliveries can be harmed (Hendricks and Singhal, 2013; Ponomarov and Holcomb, 2009; Stecke and Kumar 2009; Ponis and Koronis, 2012), in addition to the possibility of losing market to the competition (Rezapour et al, 2016) or even collapse (Xu et al, 2014). With globalization, increased competitiveness, climate and environmental changes, as well as government and economic crises, supply chains have become more complex (Hendricks and Singhal, 2005; Pettit, Fiksel and Croxton, 2010) making disruptions frequent (Resilinc, 2018). At this point, in a recent study by McKinsey (2020) executives reported that they suffered on average a severe disruption in their supply

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chain every 3.7 years and that every decade, a decrease in annual profit of around 45% can be expected.

Civil construction is a system with complex characteristics, which means that it is exposed to several social and organizational factors that can lead to instabilities, (Formoso et.al, 2021; Saurin, 2017) and, therefore, it is also subject to disruptions in the supply chain. It is therefore necessary to propose systems that are able to absorb variations and uncertainties, responding to the disturbances generated in order to minimize or even nullify the effects of these disturbances (Böhle et al 2016; Tukamuhabwa, 2015). Although little has been said about the disruption in the civil construction supply chain, showing that there is a knowledge gap that needs to be filled (Ekanayake et. al, 2021).

The phenomenon of supply chain resilience is a concept that precisely contemplates dealing with the challenges of disruption and has evolved in recent decades not only to propose ways to avoid or mitigate the effects of disruption, but to make it possible to learn from the process and in some cases allow progresses to a more efficient operational future state than the original (Shuai, Wang and Zao, 2011; Mandal, 2012; Pettit, Fiksel and Croxton, 2010, Melnyk et al. 2014). In recent years, studies in the area have identified the existence of a group of strategies that, when adopted help to mitigate the risks of disruption or to have faster and more effective responses to any disruption after it occurs, these strategies are classified into: Redundancy, Flexibility, Collaboration, Agility and Social Capital (Sawyer and Harrison, 2019; Polyviou, 2019; Pettit, et al. al 2019; Tukamuhabwa, 2015). The theme of supply chain resilience has gained space in the literature referring to several industrial sectors, however it has still been little discussed in civil construction (Ekanayake et al., 2020).

Recently, the concept of Slack was pointed out as an asset for resilience in complex systems, such as civil construction (Righi;Saurin, 2015). Bourgeois (1981) defines slack as a reserve of current or potential resources that allow an organization to successfully adapt to internal or external changes. Formoso et. al (2021) highlights that Slack has been used in the literature to describe a broad set of strategies to deal with complexity, Saurin; Werle (2017) corroborates this thought and highlights those slack strategies provide resources to adjust performance and maintain the "vital" functions of the operating system during expected and unexpected events. Fireman et al (2022) presented, from two pilot studies, a set of slack strategies applied in projects that went through a phase of disruption in the supply chain, however the study was more focused on investigating the strategies that were managed by planning and production control.

This paper aims to add clarity to the relationship of slack and supply chain resilience to answers the research question: "What are the strategies of slack and supply chain resilience theories that aim to avoid, mitigate or eliminate possible disruptions in the supply chain? Are there differences, similarities or complementarities between them?". This study is based on theoretical discussions coming from a literature review of the main papers that address strategies used in each system, highlighting similarities and complementarities so that companies can choose and apply the ones that best suit for their business environment context. Although the authors recognize that there are limitations in the literature reviews, which may not have addressed all strategies or theoretical definitions of the concepts. Finally, from the perspective of theoretical discussion, the paper provide guidance on future research on topics for the civil construction sector.

RESEARCH METHOD

The search to foster the theoretical discussion of supply chain resilience strategies consisted of finding the main systematic reviews of the literature in the last ten years using the Web of Knowledge and Google Scholar databases, for the advanced search the search string was used 'supply chain resilien* AND literature review', from the reading of the abstracts 13 papers were selected for the complete reading. Common themes of ways to perform in supply chain resilience appeared in these surveys: collaboration, flexibility, redundancy, agility and social capital. The authors then decided to explore each one of them, forming a base of 67 papers.

To verify what has been studied about supply chain resilience in the civil construction sector, the search string 'supply chain resilien* AND (civil construction OR construction industry)' was used, where only 28 relevant papers were found, indicating a possible line of research to be developed.

In the case of slack theories, the first search was carried out in the IGLC bases with the search string 'slack' resulting in 9 papers, of which 5 were selected after reading the abstract. To complement the search, the Web of Knowledge and Google Scholar databases were used again, with the strings 'slack AND (civil construction OR construction industry)', an extensive reading of the abstracts of 42 papers was made to select only 12 papers. Once again, themes common to the papers were found with regard to theoretical discussions of strategies to use slack: redundancy, flexibility and margin of manouvre.

As the two searches resulted in strategies to avoid disruption of the supply chain, so it was decided to investigate whether there are similarities, differences or complementarities between them and finally and propose a theoretical discussion.

LITERATURE REVIEW

SUPPLY CHAIN RESILIENCE

The concept of supply chain resilience has been studied with the aim of dealing with the challenges of disruption, where companies must avoid or respond quickly to disturbances and return to operational normality (Melnyk et al., 2014; Rice and Caniato , 2003) and even learn from the process and progress to an even better operational future state than the original (Shuai, Wang, and Zao, 2011; Mandal, 2012; Pettit, Fiksel, and Croxton, 2010, Melnyk et al. 2014) .

In the last two decades, studies have shed light on strategies to support supply chain resilience, whether reactive or proactive, depending on the application context (Tukamuhabwa, 2015). Sawyer; Harrison (2019); Polyviou (2019) and Pettit, et. al (2019) highlight the role of four main categories of strategy: Flexibility, Redundancy, Collaboration and Agility.

Redundancy

Redundancy is an element of the supply chain resilience strategy that involves the selective use of spare capacity and inventory to deal with supply shortages or demand variations (Parast and Shekarian, 2019). These spare capacity can be reserve stocks (Datta et. al, 2007; Pereira et. al, 2014); multiple supplier options in cases of low reliability (theme that can also be found in the flexibility strategy, but with regard to redundancy, it is related to having supplier options beyond the necessary demand and not just sharing capacity delivery between two or more suppliers, for a given demand) (Sheffi, 2001; Feng and Shi, 2012); reserve capacity of facilities, employees and modes of transport (Linnenluecke, 2017; Sheffi and Rice; 2005; Rezapour, Farahani and Pourakbar, 2016; Ponomarov and Holcomb, 2009).

Flexibility

Flexibility is a category that includes strategies that allow organizations to manage risks in the supply chain by adapting to changes in market demand or supply, causing resources to be reallocated quickly in turbulent scenarios and still maintaining performance in service levels (Tang and Tomlin, 2008; Stevenson et. al, 2008; Erol, Sauser and Mansuri, 2010; Christopher and Holweg 2011; Tukamuhabwa, 2015). Pereira et.al (2008) also points out that flexibility is a decision-making structure that allows responsiveness in the dynamics of environments.

Several strategies involving the concept of flexibilities are addressed in the literature, Tang and Tomlin (2008) list flexibility strategies in three dimensions: supply risks; process risks and demand risks. Supply risks involve multiple-supplier strategies to reduce dependence on a limited number of suppliers and flexible contracts for eventual demand adjustments, which allow changes in quantity orders between suppliers or over time (Li et. al, 2020; Wu et. al, 2019), another example can be strategies contemplating multi-modal transport (Tang, 2006). Process risks consider the flexibility of manufacturing processes or resources, such as production route alternatives due to the multi-purpose machine or even the adoption of multifunctional workers (Sheffi and Rice, 2005; Ekanayeke et al, 2021; Tang and Tomlin, 2008). Demand risks, on the other hand, are related to the flexibility of postponing production (Datta et. al, 2007) and product pricing (Zhanhai and Zhipeng, 2019).

Collaboration

Collaboration can be defined as the ability to work efficiently with other stakeholders to achieve common benefits by sharing risks, resources, information and knowledge (Parast and Shekarian, 2019; Scholter and Schilder, 2015). The collaboration strategy can contribute to reducing uncertainties inherent in the supply chain, as well as ensuring recovery in the face of a disruptive event and providing speed and agility to decision-making due to consensus between the parties (Scholten et.al, 2014).

In recent studies Duong and Chong (2020) gathered 157 literatures in a systematic review to confirm the hypothesis of the positive impact of collaboration for the recovery and response to disruptions, several collaboration mechanisms were pointed out in the authors' review, including contractual and economic practices, practices joint planning and control, relationship management, information and technology sharing, governance practices, supply chain design, and assessment and feedback practices in the post-disruption period.

A well-known example of collaboration is the case at Toyota, when Aisin Seiki's, one of Toyota's main suppliers responsible for supplying proportioning valves used in the brake system of all vehicles, suffered a serious fire. Due to just-in-time (JIT) principles, only about two or three days' worth of inventory was available. Toyota group companies, together with some external companies, immediately set up alternative production factories. The result was a feat, it was expected that the production of Toyota vehicles would stop for weeks, in just two days the plants started producing again (Nishiguchi and Beaudet 1998).

However, like most of the studied strategies, trade-offs are expected even in supply chain collaboration, Choi; Krause (2006) alert to horizontal collaboration and the risk of collusion between the parties, Jüttner; Maklan (2011) point out that there may be risks of sharing confidential information, sometimes strategic for companies.

Agility

This strategy revolves around the concept of rapid response to unpredictable changes in demand or in the supply chain (Christopher and Peck, 2004) in order to adapt, give pace and speed in the recovery of risk events (Shekarian et.al, 2020; Tukamuhabwa, 2015; Jüttner and Maklan 2011, Erol et.al, 2010).

Recent studies address the issue of technology as an increase in resilience performance through increased agility, involving blockchain, network inventories and real-time analysis, big data analytics and monitoring tools to increase supply chain visibility (Li et. al, 2022). Visibility is a key concept in the agility construct that helps to quickly identify the status of the chain and possible vulnerabilities (Tukamuhabwa et.al, 2015; Jüttner and Maklan 2011), it is closely connected with visual management and Lean Construction practices for problem solving (Saurin et al, 2021).

Social Capital

Polyviou (2019) conducts a study to explore strategies that allow small and medium-sized companies to be resilient, the author argues that companies of this size often do not have enough resources or power to use the strategies proposed so far, such as raising levels of safety stock, negotiate with multiple suppliers, and increase space, workforce, and equipment capacity. The analyzes of the study reveal other strategies in addition to those studied for large companies and that are linked to human resources, more specifically to social capital. In this point, Adler and Kwon (2002) define social capital as links or relationships between individuals or cohesive groups that seek the same goals.

The construct of social capital is formed by three dimensions: *structural capital*, *cognitive capital* and *relational capital* (Ghoshal, 1998). *Structural capital* is related to the links between actors in a given network and the patterns inherent to the links (Nahapiet and Ghoshal, 1998), examples of structural capital factors are the geographic proximity between decision makers and network size and hierarchy, in this case, the smaller the size of the network and the more horizontal the organization, the greater speed in decision-making, that is, it favors structural capital (Whittington et al., 2009; Inkpen and Tsang, 2005). *Cognitive capital* is related to the time of experience and knowledge of employees (Fischer and Pollock, 2004), and *relational capital* to team commitment, mutual respect and proximity in relationships (Nahapiet and Ghoshal, 1998).

SLACK

Slack is defined here as a reserve of resources that exceed or not the minimum necessary and that can be reallocated to support organizations to adjust performance in the face of expected and unexpected events (Fireman et al. 2022; Formoso et al. 2021; Saurin; Werle , 2017). It is possible to identify in the literature the existence of two dimensions of the slack concept, the first of which refers to which resources are being applied as slack (eg: time, equipment, projects, procedures, materials, etc.) while the second dimension is strategy-related how slack resources are being employed (Fireman et al., 2018). This paper seeks to address the second dimension, which brings the categories of strategies for the application of slack (Formoso, et al. 2021): Redundancy; Flexibility; Margins of Manoeuvre.

Redundancy

It is a category of strategy in which the resource is provided above the minimum amount necessary to perform a specific function (Nonaka, 1990), or when more than one resource performs the same function (Azadeh et al., 2016). As examples of this strategy are the redundant procedures for checking materials that must be sent to the project (Fireman et al., 2022); stock of materials (Formoso et al., 2021); and more than one foundation project considering different types of soil (Saurin et al., 2021).

In the literature on Slack, it is possible to identify four subcategories of redundancy (Formoso et al., 2021; Saurin and Werle 2017; Fireman et al.; 2022): (a) standby redundancy – strategy that deals with the adoption of resources that are not involved immediately in the running task; (b) active redundancy – when the applied resources are involved in the task; (c) redundant procedures that apply to specific cases of redundant procedures; (d) finally, the work-in-progress category, which adopts the strategy of using a backlog of available work areas (in the case of construction) or stock of semi-finished products.

Flexibility

Flexibility is seen in the literature on slack as a strategy related to the use of resources in diverse and adaptable ways (Formoso et al., 2021). At Toyota, workers' multifunctionality is naturally encouraged to absorb deviations in the production line (Shingo, 1989). Other examples of flexibility are multi-purpose equipment, flexible plant layout or even alternative sequence of production routes. The flexibility category is the most recent slack category presented in the literature (Formoso et al., 2021; Saurin, et al., 2021) which explains the low number of examples or the current lack of subcategories.

Margins of Manoeuvre

The third strategy, margin of manoeuvre, is considered a combination of the two previous strategies (Formoso et.al, 2021). It addresses the creation or maintenance of margins and additional resources that allow the system to continue to function despite unexpected demands (Saurin; Werle, 2017). Examples of this application can be seen in the study by Fireman et al (2022), which brings examples such as design changes to simplify connections in metallic parts in order to increase assembly speed; use of a reserve shift for production to correct line delays; contingency margins in the budget of suppliers. Stephens et al (2011) highlights the existence of three types of margins of manoeuvre: defensive – restrict actions of a unit or borrow margins from another unit; autonomous – local reorganization or adaptation of resources in cases of need; coordinated – creation of features that can be shared by two or more units.

DISCUSSION: SIMILARITIES AND COMPLEMENTS WITH SLACK STRATEGIES AND SUPPLY CHAIN RESILIENCE STRATEGIES

There are common points between the main strategies listed in the literature regarding slack and supply chain resilience, Table 1 represents strategies that are used for each concept. Of the six strategies presented, two themes studied are explicitly common to the slack and supply chain resilience literature: Redundancy and Flexibility. However, despite seeming to converge, apparently there are differences in the focus of action that will be commented further.

Table 1: Supply Chain Resilience and Slack Strategies

Strategies	Slack	Supply Chain Resilience
Redundancy	X	X
Flexibility	X	X
Collaboration		X
Agility		X
Social Capital		X
Margins of Manoeuvre	X	

Redundancy is a strategy that appears to have a greater degree of convergence between the two themes, it is mainly about maintaining a contingency of resources whether active or standby, as proposed by the slack literature. In the literature on supply chain resilience, although there are no clear subcategories, there are more popular examples such as capacity reserve, safety stock, backup facilities. There is a divergence regarding the role of procedural redundancy, a subcategory presents in the slack literature, but which is not identified in the supply chain resilience literature. In some situations, double-checking a critical process or supplier can be important to mitigate possible disruptions. Another important point is that the focus of slack literature has been on combating production uncertainties and not necessarily preventing a disruption in the supply chain. Examples of this are given in Saurin et. al (2021) utilizing foundation project redundancy or even reserve staff on important equipment. Fireman et. al (2018) and Saurin (2017) discuss the use of WIP (work-in-process) to have stocks of materials in different manufacturing stages, kit centers or distribution centers shared between construction trades can be examples of WIP to protect the flow production when there is instability in the production flow. These redundancy utilization strategies are more connected to production planning and control rather than supply chain resilience.

Flexibility: strategy that considers the adaptation of changes with existing resources in the company. At this point, supply chain resilience studies seem to be more advanced with regard to strategic issues to deal with supply chain demand variability and disruptions. For product pricing flexibility, for example, Tang and Tomlin (2008) cite the case of Dell, where the factory of one of its main suppliers suffered from an earthquake that compromised the delivery of components for a certain line of computers, Dell's response outside of lowering prices on other computers that did not depend on that supplier's components and thus altering demand. Behzadi et al, (2017) proposes a mathematical modeling on the multiple-sourcing strategy in the agriculture sector and concludes that this is efficient to avoid financial losses, but does not have a good performance to avoid climatic risks of harvests. Li et.al (2020) study two types of flexible contracts for risk sharing, one with the possibility of changing quantities and another with capacity reserve, they conclude that when there is no coordination in the supply chain ie - when the decentralized system does not make profits equivalent to the centralized system, these contract models perform better than contracts with less flexibility. As for issues involving operational problems, they converge in slack and the literature of supply chain resilient, such as developing skills in teams, relocation of workers to higher priority jobs, creation of alternative layouts, flexibility in changing processes to meet critical change scenarios (Saurin et.al 2021; Fireman et. al, 2022). Once again, as in the case of the redundancy strategy, the flexibility strategies used in slack seem to be more focused on the concepts of production planning and control and not on supply chain resilience. On the other hand the literature of Slack presents procedures redundancy as a subcategories of redundancy, but it is not presented on supply chain literature. Figure 1 shows the subcategories of flexibility and redundancy in the slack and supply chain resilience literatures.

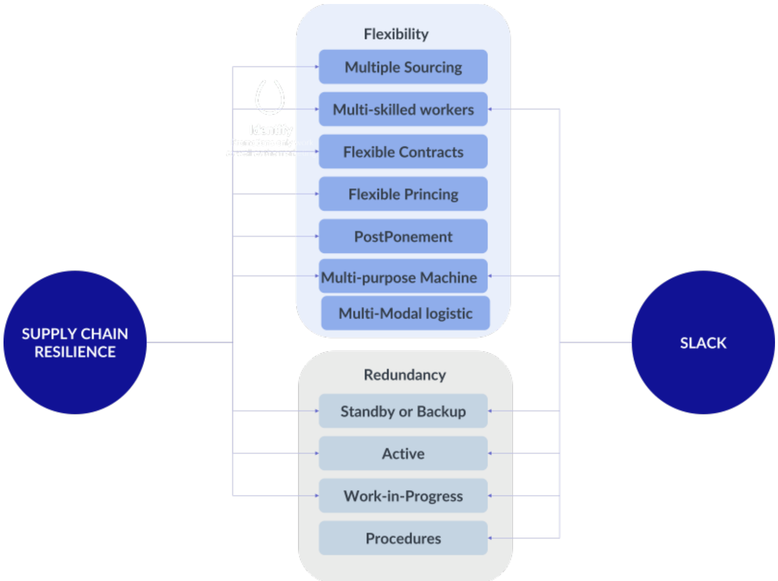

Figure 1: Redundancy and Flexibility Map

Collaboration and Margins of Manouver: It is possible to verify that there is a certain relationship between the two strategies, since the subcategories margins of manouver defensive or a coordinated it is possible to identify that there is an implicit model of collaboration, whether achieved through borrowing or sharing resources. However, the collaboration strategy has a greater focus on the supply chain external to the production environment (factory or, in the case of civil construction, the construction site), its networks of connections and development of trust, risk sharing, predictability of delivery, knowledge exchange, and postponement and resource sharing. A relevant theme for case studies involving the civil construction sector is the deepening of the trade-offs pointed out in the cited literature, to study the extent to which collaboration can be used, for example: is there any kind of conflict of interest when integrating a certain part of the supply chain? What company information can be shared with a certain network of suppliers that does not compromise the strategic advantages over the competition?

Agility: theme correlated with the use of visual management and indicators for the quick perception of problems related to suppliers, in order to detect possible threats in the chain. In the slack literature related to the civil construction sector, they point out themes that can be considered agility strategies inside other strategies, such as Saurin et al (2021) put examples of importance of daily meetings where employees detect problems to propose quick solutions and sometimes reallocated resources between teams, as defined in the flexibility strategy. Saurin and Werle (2017) still argue that visibility, a nomenclature used synonymously with agility, is a way of classifying resources.

Social Capital: strategy that enters the field of behavioral studies of human resources, there is also similarity in these resilience strategies in the supply chain with what is discussed in slack. In this point, the initial study related to slack on complex socio-technical systems presented by Saurin and Werle (2017) pointed out that discuss problem-solving techniques were classified as a category os slack strategy known as cognitive diversity. So, there is convergence with the strategy of Cognitive Capital pointed out by Polyviou et.al (2019), which aims to share knowledge of experienced employees for others. Means of measuring the performance of these strategies are still scarce in civil construction studies, as well as frameworks and case studies that shed light on how to develop these skills in human resources, with the scope to improve the effect of supply chain resilience.

CONCLUSIONS

The concept of slack is still not widespread in the civil construction sector, as well as strategies to improve aspects of supply chain resilience. Disruptions in the supply chain can be caused by external factors such as catastrophes and wars, although we must remember that these disruptions are also frequent in characteristics internal to the context of the business model, such as competition, new demands for products, relationship with the supplier network, among others. It is therefore inferred that there is a knowledge gap that needs to be taken advantage of to make companies more efficient in relation to supply chain resilience in the civil construction environment, and that they are able not only to pass unscathed through turbulent times, but that they are able to develop new ones. opportunities from them.

There are several similarities between the studies of slack strategies with supply chain resilience, theoretical definitions and discussions should be improved in order to facilitate the understanding of the topics, so companies can choose which methods and how much resources they should employ in the solutions theories without misunderstanding of concepts and duplication of applications. The present study demonstrated that there is a wide field of study on slack strategies related to flexibility, since in the resilient supply chain literature there are important subcategories that have not yet been addressed in slack studies as multiple sourcing, flexible contracts, flexible princing, postponement and multi-modal logistic. On the other hand the literature of Slack presents procedures redundancy as a subcategories of redundancy, but it is not presented on supply chain literature.

Another important point of the paper was to bring more clarity about the differences between the redundancy and flexibility strategies, which currently prove to be very close to the performance limit of each one. In this regard, it is possible to note that there is greater clarity in the supply chain literature on the difference between the two, since while the redundancy strategy seeks to work with an excess of capacity than necessary to respond to disruptions, the second has as its main objective to create capacities in existing resources to promote adjustments as demand changes occur (Xu, 2008; Datta et.al, 2007).

Finally, this study sought to confirm the importance of slack in the effects of resilience in companies, more specifically in supply chain resilience. It should also be noted that future research should study the trade-offs listed in this study to optimize their applications and choices in the desired context.

FUTURE RESEARCH

Below are some suggestions for possible future research:

- Case studies involving the application of resilience and slack strategies and lean construction mediating theses strategies.
- Performance measurement of strategies in different contexts.
- Frameworks for implementing supply chain resilience concepts adapted to the civil construction supply chain in different sectors: SMEs, infrastructure works, construction buildings, etc.

RESEARCH LIMITATIONS

Theoretical discussions are limited to current research and literature review, other concepts and discussions may not have been addressed.

Few case study examples are placed in the AEC industry, which may hinder the practical interpretation of supply chain resilience strategy concepts

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SUCCESS IN INTERRELATED SUPPLY CHAIN: AN ANALYSIS OF THE HUMAN BEHAVIOUR UNDER CRISIS

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ABSTRACT

A wealth of studies is available on the key success factors of managing interrelated projects in a construction supply chain. The human factor, however, is often overlooked in normative success solutions. According to classical management theory, individuals are expected to act rationally and maximise their utility. Although, due to an individual's computational and cognitive abilities, decision-makers often choose the first satisfactory course of action rather than searching for the optimal course of action, particularly during times of crisis. This study adopted a surrogate model to conduct a series of laboratory simulations that involved human behaviour. A comprehensive literature review was conducted to determine the experiment design, followed by sixteen hours of experiments that spanned two countries investigating decision-making behaviour within two prominent management models: the traditional and collaborative models. In order to identify patterns in the perception of the participants regarding real success factors, a content analysis was performed on their questionnaire responses. This analysis identified three key characteristics of construction success and the top characteristics required to succeed under each model investigated. By sharing these insights and lessons learned, teams can gain a deeper understanding of what it takes to succeed in a competitive environment.

KEYWORDS

Supply chain management, Simulations, Collaborative, Action learning, Collaboration.

INTRODUCTION

In the wake of the COVID-19 pandemic, the "New Normal" is characterised by a crisis-like environment, deep uncertainty, and adaptability instead of stability and long-term planning (Araya, 2021). Consequently, preparedness, recovery, and adaptation decisions must be planned and deployed in the context of concurrent disruptions (Herrera et al., 2022). To date, the impacts of COVID-19 have received considerable attention across a wide range of industries. Nevertheless, the construction sector still has much to learn about the problem and potential solutions (Cherian & Arun, 2022). As with other industries, the construction, procurement, and logistics sectors experienced unforeseen disruptions due to COVID-19's rigorous lockdowns, which also affected supply chain management. It exacerbated the chronic issues of cost

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overruns, schedule delays, and low productivity in the construction industry (Doloi, 2013; Herrera et al., 2020; Venkatesh & Venkatesan, 2017). Research indicates that improving the product development process, supply chain coordination, and the standardisation of parts and components can mitigate the impact of these recurring issues. In order to achieve these goals, the importance of improving client-contractor interactions cannot be overstated, particularly through establishing strategic alliances and partnerships that facilitate real collaboration (Chen et al., 2012; Dainty et al., 2001; Engebø et al., 2020; Lahdenpera, 2017; Mesa et al., 2019).

Lean emphasises collaboration, supported by process ontology, to address the interrelationships between tasks (Tzortzopoulos et al., 2020). The success of any collaborative approach depends on the participation of individuals. While normative solutions are often used to achieve operational goals, they tend to rely on simplistic behavioural assumptions that fail to take into account the complexity of human behaviour (Ghodrati et al., 2022; Gino & Pisano, 2008; González et al., 2015). The classical economics theory typically assumes that individuals act rationally and make decisions to maximise their utility (Parnell & Crandall, 2020). However, rationality is bounded by human computational and cognitive capabilities (Selten, 1990). Consequently, decision-making patterns in projects are often inconsistent with normative theories, especially in complex situations (Kahneman et al., 1982). In 1957, the concept of bounded rationality was introduced (Simon, 1957). The approach emphasises effective behaviour rather than an idealised state of perfect rationality. Informational inadequacies, time constraints, and cognitive limitations all contribute to the inability to make perfect, rational, and well-informed decisions. (Diacon et al., 2013). It is, therefore, more likely that in times of crisis, a satisfactory or suitable decision will be reached in which the decisions are adequate but not perfect. (Parnell & Crandall, 2020). When faced with such circumstances, decision-makers often choose the most suitable course of action instead of continuing to search for the optimal course of action (Fox, 2015).

Our primary objective in this study was to explore how behavioural patterns in decision-making can be linked to the construction supply chain dynamics, especially during a crisis. This research belongs to the behavioural operations management field and adopts a laboratory-based experimental strategy applied in a number of social science fields, including economics, psychology and sociology, law, political science, anthropology and biology (Katok, 2019). There is a high cost and/or disruption associated with investigating the influence of human behaviour on collaboration dynamics in a real system under a variety of conditions. A laboratory experiment can simulate a situation while isolating the intended variables from the rest. Laboratory experiments became mainstream research setting in social science in 1875. It was not until the 1980s that operations management research began to take it up. As a result, surrogate models are the preferred approach for laboratory simulations. They allow a complete manipulation of all factors to match the study assumptions (Bolton & Ockenfels, 2008).

RESEARCH DESIGN

The overall research design is presented in Figure 1. The study started with an extensive literature review to identify the experiment design. The experiments were conducted in two countries over four days, consisting of two rounds each day. In the first round, all participants acted independently, simulating the traditional supply chain management model. Participants adopted a collaborative approach in the second round, in which they agreed to work together to achieve a specific objective. The decision behaviour patterns of participants were recorded and analysed based on their perceptions. To obtain participants' perceptions regarding their experiences under each model, a questionnaire was administered after each round. Upon completion of day 4, a content analysis was carried out to identify patterns in the recorded results. By conducting the same experiment in two different countries, we were able to detect any cultural nuances that might have impacted the results.

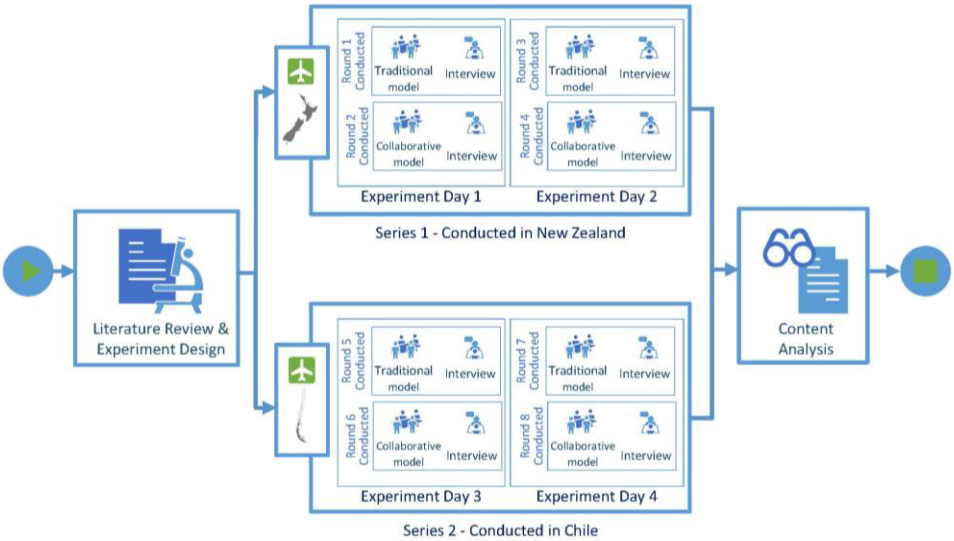


Figure 1: The research design

THE EXPERIMENT STRUCTURE

The experiment simulated a simplified version of the supply chain for five bridge construction projects, including prefabrication and shipping stages. Figure 2 shows the entities and relationships involved in creating a conceptual model of a system according to the standard steps (Abdelmegid et al., 2017; Abdelmegid et al., 2020; Poshdar et al., 2016). A total of six individuals representing key members of the supply chain participated in the experiment.

- Two participants represented the manufacturers responsible for fabricating the structural components (Fabricator 1 and Fabricator 2).
- Two participants represented transportation agencies responsible for delivering prefabricated components to the construction site (Shipping 1 and Shipping 2).
- Two participants represented contractors involved in the construction project (Contractor 1 and Contractor 2).

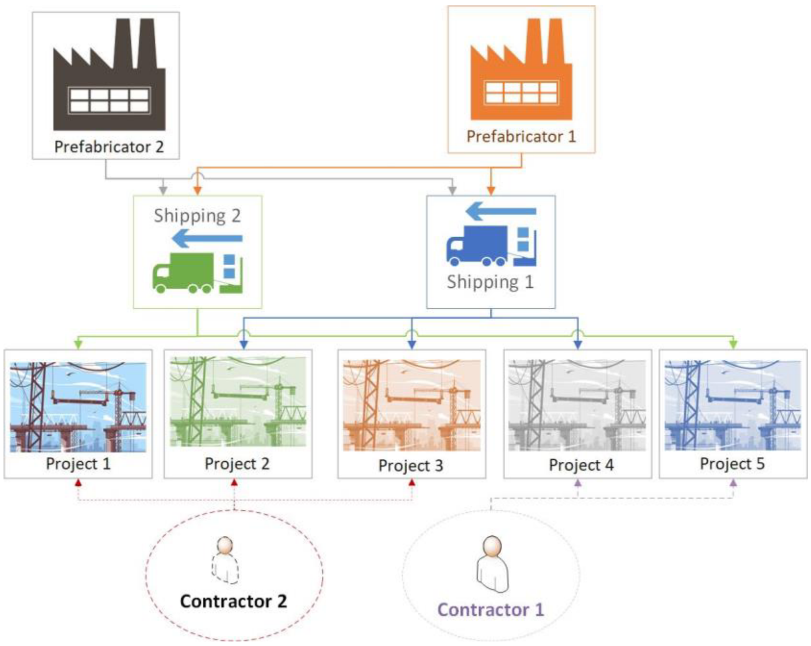


Figure 2: The experiment structure

The bridge components were those recommended by Waka Kotahi, the New Zealand Transport Authority. Detailed information about the simulated projects is presented in Table 1.

Table 1: Characteristics of the projects simulated.

Project #	Number of beams	Type of beams	Span length (mm)	Shipping distance (km)
Project 1	9	Single hollow core beam, 900 mm Depth	25,000	450
Project 2	5	Super T beams	30,000	86
Project 3	4	Single hollow core beam	27,500	242
Project 4	9	Single hollow core beam, 650 mm Depth	18,000	91
Project 5	9	Single hollow core beam, 650 mm Depth	16,000	408

A rough budget was assigned to each activity based on the size of the project and shipping distance (Table 2).

Table 2: Budgets allocated to each activity within the supply chain divided by projects.

Project #	**Prefabrication ($)**	**Transportation ($)**	**Construction ($)**
Project1	277,000	208,000	2,079,000
Project2	277,000	46,000	2,703,000
Project3	185,000	46,000	2,657,000
Project4	277,000	46,000	1,409,000
Project5	277,000	116,000	1,409,000

A 10% contingency was built into the quantity take-off price in the budget. The calculated prices are summarised in Table 3.

Table 3: Summary of activity costs.

Costs Associated	**Prefabrication** ($ Per week)		**Transportation** ($ Per week)	**Construction** ($ Per week)						
	Line set up.	Operations	Operations	Site Establishment	Staging Installation	Precast Beam	Deck	Parapet	Remove Staging	Urban Design & Walkways
Direct cost	8,000	68,000	9,000	120,000	40,000	40,000	70,000	20,000	70,000	30,000
Overhead	2,000	2,000	1,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Total	10,000	70,000	10,000	130,000	50,000	50,000	80,000	30,000	80,000	40,000

Each participant could face two types of delays to imitate real-life pressure on a decision-maker.

- Normal delay that its likelihood was between 6% to 10%, which was implemented as a randomly generated number for each activity.
- A pandemic delay would apply a locked-down period with an arbitrary length of between 5 and 10 weeks. The purpose of this study was to examine the decision-making behaviour of supply chain members during times of crisis. Therefore, all experiments involved the delay caused by a pandemic.

THE EXPERIMENT PROTOCOL

Each round of the experiment involved the following five steps:

Step 1 - The facilitator described the experiment structure and rules, allocated roles and funds. The roles were assigned randomly, and participants remained with the same role for the whole experiment. A random number generator was then used to determine the length and the start week of the delay caused by the pandemic. The participants were not informed about this latter information until the due week.

Step 2 – Participants started planning their operations. They could decide when to start each activity to minimise costs and maximise profit. However, once it had begun, they could not stop overhead payments or add additional working shifts to speed things up. The reactive approaches were restricted in order to avoid an overwhelming level of complexity.

Step 3 – The experiment set the time unit of the operations as weeks. The facilitator would announce the start of each week while running a random number generator to identify and inform the participants about the typical delay for each activity. The players would implement their plan accordingly, and the costs were deducted per operating over a week.

Step 4 – A full round of the experiment finished when all participants had their activities completed.

Step 5 – A questionnaire with the following five open-ended questions distributed among the participants. It was used to assess participants' perceptions of the factors that influenced their decision patterns, and those that could contribute to their success under each model.

- Did you find any operational strategy useful to achieve success in the collaborative phase?
- What would you do if, at some point, your profit opposed the team's benefit under the collaborative model? Have you ever encountered such a situation in this experiment?
- What are the top five characteristics that can help a player succeed in a collaborative environment? Why?
- What are the top five characteristics that can help a player succeed in the traditional model? Why?

Although we provided some examples for questions 3 and 4, participants were given the autonomy to include any items they deemed relevant.

The criteria for success in these experiments were defined based on two common Key Performance Indicators (KPIs): time and cost. The measurement of success was based on the achievement of these criteria. In order to create personal incentives, in each round, the participant who could achieve the highest ratio of earnings to the allocated budget would receive a 30$ voucher and a bar of Chocolate.

IMPLEMENTATION OF THE EXPERIMENTS

During April and May 2022, four rounds of experiments were carried out in New Zealand, two simulating the traditional model and two simulating the collaborative model. Twelve undergraduate engineering participants participated in this series. In August and September 2022, the same four rounds of simulations were conducted with 18 undergraduate civil engineering participants from Chile. A random sampling approach was used to select the participants. Since each individual in the population had an equal chance of participating, regardless of their characteristics or traits, this approach ensured a reduced bias in the results.

The experiment took an average of two hours for each round. Thus, a full experiment day took around four hours, and a total of sixteen hours were spent conducting the experiments for this study. All decisions and movements made by the participants were recorded using a spreadsheet. The following is a breakdown of the average completion length (in nominal weeks) recorded for each project: Project 1: 45; Project 2: 41; Project 3: 36; Project 4: 25; Project 5: 31.

RESULTS AND DISCUSSION

The first question invited participants to reflect on their experiences and identify strategies that proved effective in achieving success.

The result: Communication and coordination were among the most frequently recorded success factors. *The Discussion:* Transparent communication from the beginning of projects was indicated to be crucial to planning and minimising downtimes. A well-coordinated strategy is essential for the success of any team effort. In a competitive environment, this is even more critical. Additionally, the participants stressed the importance of teamwork and collaboration when prioritising activities. Working together to identify long-term goals helps ensure that all team members work towards a common goal and can prioritise their activities accordingly (Zulch, 2014). In order to achieve success, the participants also suggested that an initial kick-off meeting could be an instrumental step, as it can enable discussion of strategies and the development of agreements with others. These meetings allow all shareholders to discuss strategies and reach agreements about the common goal.

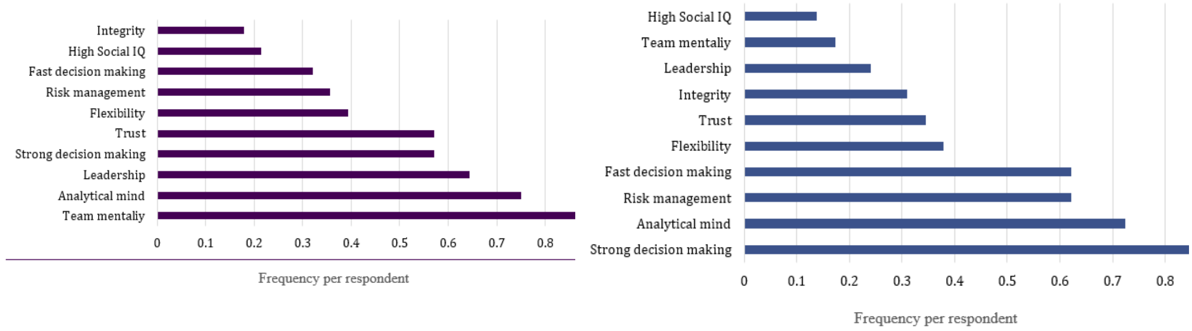
Managing projects effectively requires a global and systemic understanding of operations and supply chain members. With a global perspective, managers can identify areas where costs and delays can be reduced. Additionally, by having a systemic view of the supply chain, they can assess potential risks and plan accordingly to ensure that the project is completed on time and efficiently. To involve a systemic understanding in project management, managers should create a detailed map of the entire supply chain, identify bottlenecks, and analyse the dependencies between each supply chain member. It will help them to identify opportunities for cost savings, as well as potential areas of risk. Additionally, they should create a timeline for the entire project and ensure that all stakeholders and supply chain members know their responsibilities and deadlines (Chou & Yang, 2012).

The result: In addition, the participants stressed the importance of mutual agreement and trust between all parties to achieve success. *The Discussion:* In order to ensure that the project is completed effectively, it is imperative to build trust and establish positive relationships between all parties. It ultimately reduces disputes, reduces costs, and increases overall project success. These relationships should be maintained throughout the project timeline to ensure everyone is on the same page and working towards a successful outcome. Trust can be built through regular meetings between parties to review progress and discuss any potential issues or risks. Additionally, creating a safe and open environment where people can share their ideas, concerns, and feedback is another way to establish trust and build strong relationships (de Oliveira & Rabechini Jr, 2019; Karlsen et al., 2008).

The second question presented a thought-provoking dilemma for the participants, testing the balance between personal gain and team success. Having personal interests that conflict with team benefits is a real-life scenario that can occur in a variety of contexts, including construction.

The result: The answers show that the participants understand the importance of teamwork for achieving success under a collaborative model. Participants prioritised common benefits and collaboration in decision-making, while also emphasising the importance of optimising the global project and synchronising agents. Despite the potential for individual gains, sacrificing personal gain for the greater good of the team was seen as critical by the participants, who displayed a high level of integrity in choosing the team's benefit over their own profit. *The Discussion:* The participants' emphasis on prioritising common benefits, collaborating in decision-making, and sacrificing personal gain for the team's benefit are in line with the literature on effective team dynamics and collaboration. The collaborative model, in which parties share profits, risks, and responsibilities, is becoming increasingly popular in the construction industry as a means of fostering collaboration and improving project outcomes (Anvuur & Kumaraswamy, 2007; Elghaish et al., 2020; Giménez et al., 2022; Lahdenperä, 2012).

It is paramount to possess certain key characteristics to succeed in the collaborative model in the construction and project management world. It led to the third question covering the top qualities of success in the collaborative model.



(a) The collaborative approach

(b) The traditional approach

Figure 3: The perspectives about the success factors

Figure 3 (a) summarises the ideas based on the frequency of occurrence in the responses to question 3.

The result: According to the participants, team mentality and approaching the project as a collective effort were the most relevant characteristics for success in a collaborative environment. *The discussion:* When the team is united, they can share ideas and resources more effectively and better understand each other's strengths and weaknesses. It allows them to better coordinate tasks and collaborate on solutions (Mack et al., 2008).

The result: A strong analytical mind was found to be among the top three important factors to success for participants. It allows them to assess situations, identify potential problems, and make informed decisions. *The discussion:* teams need to understand better the problem and the resources available to find solutions more effectively. Analytical skills can assist teams in resolving problems more effectively, creating a more harmonious environment that facilitates achieving the desired results (Asfar et al., 2021).

The result: Participants ranked leadership as the third most influential factor that would lead to success. *The discussion:* It involves leading the team to achieve common goals, making decisions, and resolving conflicts. Effective leaders can motivate the team, inspire them to work together, and set a positive example. They can listen to the team and consider their opinions when making decisions. They can also manage conflicts effectively and maintain a healthy work atmosphere (Nishizaki & Seed, 2015). There was some difference between the identified success factors of the traditional model and those of the collaborative model. **Error! Reference source not found.**(b) summarises the answers to the fourth question regarding the success factors of the traditional model based on the frequency of items among the responses.

The result: In the eyes of our participants, strong decision-making stood first among all other success factors. *The discussion:* The construction sector often involves a considerable amount of decision-making, risk assessment and quick thinking. It is particularly critical to developing these skills in traditional models. In the model, individuals are valued for managing risks effectively and coming up with smart decisions (Flyvbjerg, 2021). Therefore, it is crucial to have strong decision-making skills, as decisions are expected to be reached quickly and effectively without the support of a large team.

The result: Strong decision-making skills are crucial in the traditional model, as participants are expected to make quick and effective decisions without relying on the support of a larger team. *The discussion:* A strong analytical mind was also listed as one of the three most important characteristics of success in this model. An analytical mind helps individuals better understand the world's complexities, identify patterns, and make informed decisions that can lead to greater success (Alvarenga et al., 2019).

The result: Risk management has been identified as one of the top three success factors in the traditional model. *The discussion:* A thorough understanding of the construction industry and a strong ability to assess risks and evaluate potential outcomes are required for supply chain members to assess risks, evaluate potential outcomes, and make decisions accordingly. Risk management can assist in identifying and resolving upcoming problems before they become issues. Moreover, it can minimise the negative effects of any risks that may occur and ensure that the project remains on schedule and within budget (Micán et al., 2020).

The result: Both the collaborative and traditional models in the construction industry emphasise analytical mind but require different specific traits for success. The collaborative model emphasises team mentality and leadership, while the traditional model emphasises strong decision-making and risk management.

The result: Most participants preferred the collaborative model over the traditional one to achieve success when asked after the experiments. The main reason for this preference was the ability to better coordinate and communicate with their peers, which led them to make more effective and efficient decisions which could result in lower risk-taking. Participants believed collaboration and teamwork could improve workflow, reduce costs, and achieve better results. The collaborative model, according to them, also contributed to more equitable profit distribution and improved performance. Additionally, participants noted the importance of sharing information and risks, as well as enhanced synchronisation, which contributed to their success. Overall, participants reported that the collaborative model provided better coordination, communication, and cooperation among all members, resulting in faster, more efficient, and more successful outcomes.

The result: Although there were some differences in frequency between the two countries, the items and their order followed a similar pattern. It suggests that the findings were largely independent of the work environment in the two countries, providing an accurate comparison for further research.

CONCLUSIONS

Using a laboratory experiment methodology, behavioural operations management research was conducted to examine how decision-making behaviour patterns and crises impact typical construction supply chain members. We conducted four days of experiments in two countries, each with two rounds. A traditional work model was simulated in the first round, while a collaborative approach was tested in the second round. After the administration of a questionnaire and a content analysis, several key points were identified.

When comparing the collaborative and traditional models of managing supply chains in the construction industry, it is evident that both models prioritise certain key characteristics, such as analytical thinking. However, it is imperative to note that each model requires different characteristics to succeed. The collaborative model emphasises team mentality and leadership. In this model, it is essential to have a team player who collaborates with others. Any team member should be able to prioritise the team's benefit over their interests. Additionally, effective team leadership and management practices can facilitate team cohesion and support collaborative project management efforts.

On the other hand, the traditional model emphasises traits such as decision-making ability and risk management ability. In this approach, various stakeholders are expected to work independently. It is essential for individuals to possess strong decision-making skills and manage risks independently. Effective decision-making involves evaluating multiple options and choosing the most appropriate course of action based on relevant information, while risk management involves identifying and mitigating potential hazards and uncertainties.

Sharing insights and lessons learned from these experiments contributed to developing a collective understanding of what it takes to succeed in a competitive environment. Teams seeking to improve their performance and achieve their objectives can benefit from this information.

This study presents the first step in developing a laboratory experimental approach to investigating management strategies. There were some limitations to this study regarding the number of experiments, the number of models tested, and the sampling criteria for participants. Therefore, further research is required to verify the reliability of the results. During future research, experiment sizes will be increased, and new models will be tested using different sampling criteria for participants. Cognitive errors may also have negatively affected the results. For example, trust, team mentality and integrity are three concepts susceptible to being confused in participants' minds. In order to accurately measure data, it is critical to define reliable indicators for each concept. To determine the impact of these factors separately, it would be appropriate to focus on one concept at a time. It would ensure that the data collected is specific to that concept and not impacted by any other concepts being studied. It will help to minimise ambiguity and ensure that the data accurately reflects the intended meaning of the concepts.

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DEVELOPMENT OF AN OPTIMIZATION MODEL BASED ON BUSINESS PROCESS RE-ENGINEERING TO MINIMIZE CONSTRUCTION PROJECTS DELAY

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ABSTRACT

Related decisions can affect project scheduling in a construction supply chain (CSC). After all, the project activities require vital resources and collaboration among project stakeholders. That effects can occur negatively, such as delay, budget overrun, and project performance. These effects are considered wastes in lean construction (LC). The concept of LC is still limited regarding application in CSC. This study aims to develop a decision-making model (LC tool) to minimize project delays using a mixed integer linear programming optimization model. The proposed model is triggered by the business process re-engineering of the scheduling process.

A construction company case example that delivers construction renovation projects to its customers is considered for validation. This approach is applied in two stages. In the first stage, the information process flow of the company is developed to derive the inputs required for the logistics and scheduling optimization model. Then in the second stage, the mathematical model is developed based on the inputs to generate optimal supplier selection, projects schedules, and resource utilization decisions. By using the proposed LC tool, the results show that delays in multiple projects can be minimized. Finally, decision-makers can use this technique to manage concurrent projects and suppliers that leanly provide essential resources to these projects.

KEYWORDS

Lean Construction (LC), Construction Supply Chain (CSC), Optimization, Offsite Construction, Scheduling

INTRODUCTION

Lean construction (LC) or lean manufacturing focuses on the constant effort of removing waste, meeting or exceeding all customer expectations, focusing on the entire value chain, and

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increasing efficiency or productivity in the execution of a construction project or manufacturing process (Eldeep, Farag, & Abd El-hafez; Mossman, 2018) and (Zimmer, Salem, Genaidy, & Shell, 2008). The lean theory has five fundamentals: value, value stream, flow, pull, and perfection. The lean philosophy aims to increase customer value while eradicating waste. Lean construction considers the construction processes as a flow of activities, and all non-value-adding activities are considered as "waste" (Eldeep et al., 2022).
The objective of lean philosophy is to minimize waste. In LC, the activities or events considered as "waste" are defects, overproduction, waiting, over-utilized talent, transportation, inventory, motion, and extra processing (Igwe, Hammad, & Nasiri, 2022). Therefore, any approach or tool that minimizes these wastes can be considered an LC tool. Based on the literature, LC tools for construction supply chain management (CSCM) can be qualitative such as just in time (JIT), or only quantitative such as mathematical optimization (Uriarte, Ng, & Moris, 2018), or hybrid method (Li, Fan, & Wu, 2010).

CSCM manages communication and actions among project stakeholders who collaborate to ensure appropriate responses to the varying demand and supply signals across supply chain functions (Mello, Gosling, Naim, Strandhagen, & Brett, 2017). An efficient construction supply chain (CSC) enables cost savings, schedule compression, decreased material lead time, and high-quality construction projects (Le, Elmughrabi, Dao, & Chaabane, 2020). CSCM is a promising approach to successfully integrating several internal and external players (suppliers, designers, vendors, contractors, subcontractors, and internal and external clients) (Le, 2020).

Lean supply chain management is an important field of research. Different frameworks have been proposed and applied successfully in many industries (automotive, retail, etc.) and service sectors (healthcare, financial, etc.) (Jasti & Kodali, 2015). Lean and construction supply chain management needs a better understanding ((Le & Nguyen, 2022) ; (Zimmer et al., 2008)). More research will help develop LC tools that improve CSC at different construction project phases and deal with CSC issues, such as delays in projects in both breadth and depth (Liu & Lu, 2017). Therefore, this research proposes a lean construction tool to minimize delays in construction project scheduling activities by combining two Lean supply chain management pillars: business process re-engineering (Information technology) and logistics optimization (Logistics Management).

LITERATURE REVIEW

CSCM is a popular and emerging topic. A recent literature review study shows six established research clusters: logistics and SCM for prefabricated construction, construction procurement, CSC integration, green construction SCM, reverse logistics in construction, and onsite construction logistics (Nguyen & Le, 2022).

Hatmoko & Scott (2010) defined construction SCM as a system where suppliers, contractors, clients, and their agents work together to install and utilize information to produce and deliver materials, plant, temporary works, equipment, labor and/or other resources for construction projects. The concept of the construction SCM implicitly provides the opportunity for substantial improvements in client and stakeholder value through a strategic look at profitability. Lean construction is more effective if it integrates with supply chain collaboration, especially long-term collaboration. In other words, supply chain collaboration facilitates lean application and accelerates lean transformation (Meng, 2019)

Lean construction(LC) provides principles and tools that support companies to recognize and remove non-value addition activities or tasks from processes, improve productivity, and provide value to customers. Optimum results could be obtained by continuously striving for improvement (Plenert, 2011). LC can work with other construction technologies, and there is an increase in the integration of (LC) and Building Information Modelling (BIM) to derive benefits(Marte Gómez, Daniel, Yanquing, Oloke, & Gyoh, 2021). There is little literature regarding applying business process re-engineering and mathematical optimization to achieve lean construction (LC) in CSC. The following table shows the search results of different keywords used in the Scopus database.

Table 1: Search Keywords Result

Query	Keywords	Results
1	lean construction AND supply chain AND scheduling	22
2	lean construction AND supply chain AND performance improvement	30
3	supply chain AND lean construction AND business process AND optimization	6
4	supply chain AND lean construction AND business process AND optimization AND scheduling	2

The two papers combining the fourth query keywords do not focus on CSC, and the papers resulting in the third query keywords combination is six. Out of six, only two were relevant to CSC. They developed a software platform system and integrated project stakeholders and Building Information Modelling (BIM) technology to collaborate to achieve lean construction digitally and improve project performance collectively (Yungui, Kuining, Yongbin, & Tao, 2014). One study proposed a methodology to integrate principles of lean construction and constraints of resource scheduling into a constraint programming optimization formulation to improve construction productivity and logistical efficiency (Liu & Lu, 2017).

Some papers deal with construction supply chain optimization, including supplier selection and minimization of project delays. However, none are linked with lean construction, as evaluated above in the literature search results.

For the mathematical model to give output, it requires input data, which are parameters. This paper applies LC methodology to minimize waste and attain the parameters necessary to minimize project delays. Some papers applied optimization in construction project scheduling and supplier selection.

Mirghaderi & Modiri (2021) developed a heuristic-based multi-objective mathematical model under uncertainty investigated for construction material supply chain design. The considered supply chain comprises a primary supplier and a number of projects (i.e., customers) demanding different construction materials in different periods depending on the technical specifications of the demanded product in terms of lifetime.

A mathematical model is conceived in this study to design and optimize risk-averse logistics configurations for modular construction projects under operational uncertainty. The model considers the manufacturing, storage, and assembly stages, along with the selection of optimal warehouse locations, but supplier selection was missing in their model(Hsu, Aurisicchio, & Angeloudis, 2019).

García-Nieves, Ponz-Tienda, Ospina-Alvarado, & Bonilla-Palacios (2019) proposed a mathematical model that practitioners can easily use to optimize construction schedules considering to the largest extent the time and space conditions repetitive projects offer.

RESEARCH METHOD

This section provides details of the problem and justification of the solution proposed to solve the problem.

PROBLEM DESCRIPTION

A construction consultancy company based in Montreal, Canada, delivers construction projects modular or traditional for Canada based in Montreal. We named the company XYZ in this paper to protect their privacy. The XYZ company provides optimal foundation and structural repair solutions as well. The problem they faced was assigning resources to different projects and managing different project schedules. They were looking for mathematical solutions to optimize their project scheduling and assignment of resources to multiple projects. Initially, they did not have any process mapping of their processes, and many processes needed to be more varied or waste that did not add any value to their work.

SOLUTION APPROACH

The reason for choosing the business process management (BPM) technique to identify redundant processes is that it helps to align your strategic objectives with business processes, demonstrate executive commitment, and empower employees. The chances of improvement in business processes will be amplified (Hung, 2006). The BMP technique helped the XYZ company set its lean objective to minimize multiple project completion times.

To optimize the project schedules, different techniques can be applied. We selected a single-time minimization objective because the single-project approach identifies better solutions than the multi-project approach. (Kannimuthu, Raphael, Ekambaram, & Kuppuswamy, 2020). We selected solver-based optimization over simulation-based optimization for project scheduling because it is fast convergence (for small problems), time constraints modeling, and makes exact solutions possible. In contrast, in simulation, it is slow convergence and not always the optimal solution reached. (Klemmt, Horn, Weigert, & Wolter, 2009).Therefore in this research, we utilize both BPM and mathematical optimization techniques to achieve the best results.

MODEL DEVELOPMENT METHODOLOGY

The mathematical model is developed in two steps to achieve LC (minimize project delay). First, the business process of XYZ is studied and improved based on the information required as inputs to minimize delays in their ongoing project schedules.

After fixing their business process information flow, a mixed integer linear programming mathematical model is developed to minimize the project delays based on supplier selection and project activities optimization. The explanation of these steps is shown in Figure 1.

The first step concerns improving the organization's information flow process to gather inputs for the mathematical model. The second step is related to mathematical model implementation and the generation of optimized schedules.

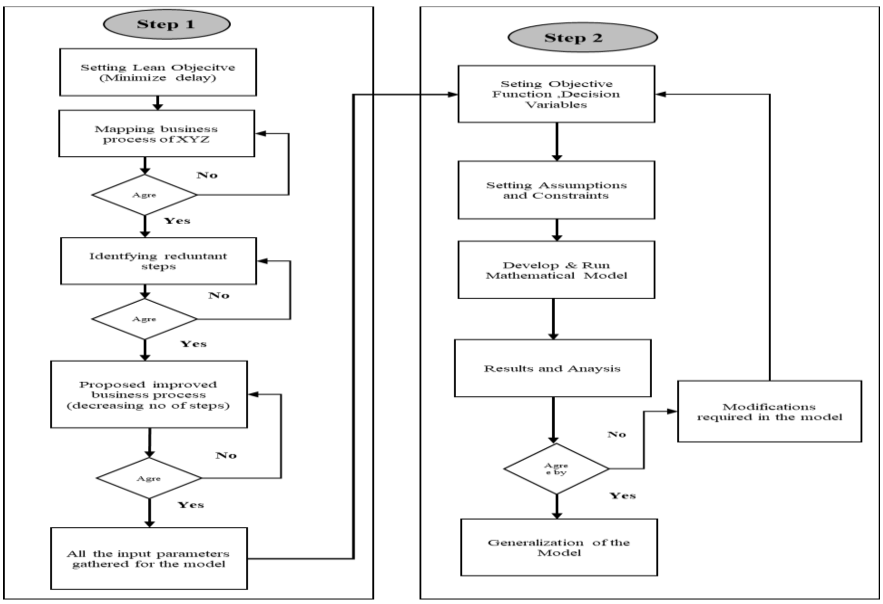

Figure 1: Working Methodology

FIRST STEP IMPLEMENTATION

The company's business process is analyzed and improved in the first step to get the required data to generate schedules. The following figure 2 shows company XYZ's proposed information flow process for managing schedules. There are two departments: administration and technical, along with three people involved in generating and managing schedules of projects. The company manager is from the administration department, and the project manager and team lead are from the technical department. The information flow system is integrated, and the information, whether input or output of the process, is shared by these three people through an IT system named the scheduling system in the figure.

The information generated in these processes includes the number of projects scheduled to optimize, the type of resources required for the project, supplier's information, project activities duration, cost of resources by suppliers, activities precedence to each other, and due date of project completion. These inputs are shown in green borders in the below figure. This input information will be stored in an integrated system that will allow them to manage and view it. The "XOR" gate used in the team lead pool shows the decision he has to take for the resources. If the company has enough resources for the project, it will proceed without suppliers. Still, if company resources are insufficient, he has considered the cost and time associated with suppliers for providing resources. This paper considers projects that require supplier resources for their completion. Then after receiving the input information from the team lead about the projects, the project manager will assign relative importance weights to these projects based on priority. These weights will be critical as the model in the second step will optimize the project schedules based on these weights.

After having this information, the project manager will finally use the mathematical model to generate optimized project schedules in real time. This administration and other departments will receive updated information about the project schedules, as shown in the last process of Figure 2.

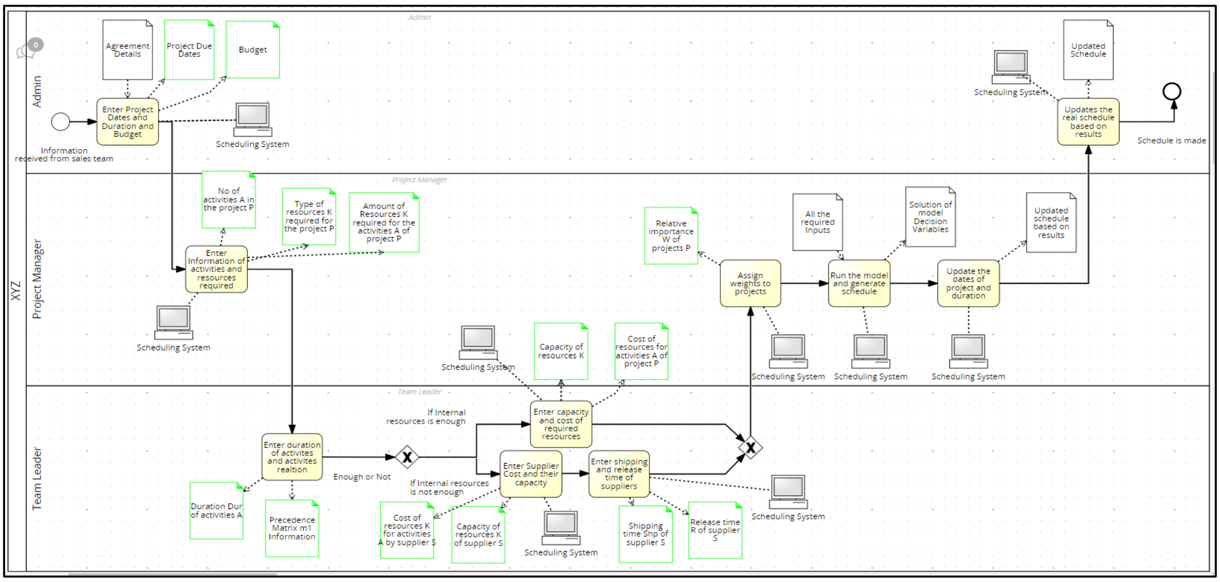

Figure 2: Proposed XYZ Information Flow Process for Managing Project Schedules

SECOND STEP IMPLEMENTATION

A mixed integer linear programming model is developed to optimize project schedules. This model is inspired by the study of (Chen, Lei, Wang, Teng, & Liu, 2018) with small modifications such as adding a precedence matrix approach as a constraint. The assumptions taken for this model include the following: projects are independent of each other regarding activity dependence, but they can share suppliers and resources. No uncertainty factors are included in the model; the raw materials are always available in the right quantities in the supplier's warehouse; they do not produce a surplus, and the elements are transported in shipments whose sizes were fixed before.

The details of the model are given as follows:

Sets)

P	Set of Projects
S	Set of Suppliers
A	Set of Activities within each Project
K	Set of Nonrenewable Resources

Parameters)

Q_{PAK} Quantities required by each activity A of each resource K of each project P

Cap_{SK} Total capacity of each supplier S for resource K

R_{SK} Release time of supplier S for resource K

Shp_{SP} Shipping time of supplier S to project P

Co_{SKA} Supplier S cost of supplying resource K

Dur_{PA} Duration of activity A of project P

W_p Relative weight of project P

DD_P Due date of project P

$Bud = \$10000$

$M = 50000$

m_P The precedence binary matrix for each activity of project P

Decision Variables)

X_{PSAK} Binary variable representing the supplier selection for resource k of activity A of project P

Z_{PSAK} Quantity supply of resource k for activity A of project P by supplier S

ST_{PA} Starting time of activity, A of project P

TD_P Tardiness (delay) of project P

CT_P Completion time of project P

Objective Function)

The objective function is to minimize the delay of multiple projects simultaneously based on their importance weights.

minimize $$\sum_{p} W * P \tag{1}$$

Constraints)

$$\sum_{p \in P} \sum_{a \in A} Z_{pska} \leq Cap_{sk} \forall s \in S, k \in K \tag{2}$$

The equation 2 constraint is related to the capacity of the supplier. Each supplier has different capacity for resource k and its total supply for each resource must be equal or less than its capacity.

$$\sum_{s \in S} Z_{pska} \geq Q_{pak} \forall p \in P, a \in A, k \in K \tag{3}$$

The equation 3 constraint is related with quantity of resources k required by each activity. The total units of resource k supply by supplier S should be greater than or equal to required quantity of activity a of project p

$$\sum Z_{pska} \leq M \times X_{psak} \forall p \in P, a \in A, s \in S, k \in K \tag{4}$$

The equation 4 constraint is related to big M. It implies that the quantity of resources k should only be supplied by supplier s that are selected for that activity a.

$$\sum_{p \in P} \sum_{s \in S} \sum_{k \in K} \sum_{a \in A} Z_{pska} \times Co_{ska} \leq Bud \tag{5}$$

The equation 5 constraint is related with budget of projects. The total cost of resources k required by activity a of project p should be less than or equal to the budget.

$$\sum_{s \in S} (R_{sk} + Shp_{ps}) \times X_{psak} \leq ST_{pa} \forall p \in P, a \in A, k \in K \tag{6}$$

The equation 6 constraint is related to release time, shipping time of supplier *s* of resource *k* and starting time of activity a. The starting time of activity a should be greater than or equal to the summation of release and shipping time of supplier *s* for resource *k*.

$$ST_{pa} + Dur_{pa} \leq CT_p \forall p \in P, a \in A \tag{7}$$

The equation 7 constraint is related to the construction time completion of the project. The starting time of the last activity of project p and its duration must be less than or equal to the construction completion of the project.

$$TD_p \geq CT_p - DD_p \forall p \in P \tag{8}$$

Equation 8 is related to the tardiness of the project. It states the difference in time between the due date of the project(input) and the construction completion of the project (decision variable).

$$ST_{pi} + Dur_{pi} \leq ST_{pj} \forall p \in P, i \in A, j \in A, i \neq j \tag{9}$$

Equation 9 is related to precedence matrices of projects. It provides information on activities dependence on other activities via binary format.

IMPLEMENTATION

All the input parameters are fed into the Python model through Excel sheets. Some of these are shown below. The relative importance weights W of projects chosen randomly as P1 = 0.4, P2 =0.2, and P3 = 0.4. Each project has its precedence matrix, and in Table 2, the precedence matrix, namely "m1" of project 1 is shown below. This table is read as horizontal number depends upon vertical number; for example, in the table, activity 2 is dependent upon completion of activity 1 and similarly, activity 7 is dependent upon all activities from 1 to 6 and will not start until these activities are complete.

Table 2: Precedence Matrix for Activities of Project 1

m1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1		1					1											
2							1											
3							1											
4							1											
5							1											
6							1											
7								1										
8									1									
9										1		1						
10											1	1						
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Another input Q, the resources required by activities of different projects are shown in Table 3. This parameter is in three dimensions where "A" represents activities of a project, "K" represents resources required for that activity, and "P" represents projects.

Table 3: Resources Required by Activities of Different Projects

		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18
P1	K1	5	4	4	5	4	4	5	4	4	5	4	4	5	4	4	5	4	4
P1	K2	2	6	1	2	6	1	2	6	1	2	6	1	2	6	1	2	6	1
P1	K3	5	0	2	5	0	2	5	0	2	5	0	2	5	0	2	5	0	2
P2	K1	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
P2	K2	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4
P2	K3	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0
P3	K1	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5	3	4	5
P3	K2	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4	4	8	4
P3	K3	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0	6	0	0

RESULTS

The optimization model for logistics management was implemented using Python and solved with the Gurobi solver. The model generated contains 986 constraints and 1,086 variables (486 binary variables, 972 integer variables, and 372 continuous variables). Solutions for the different cases are obtained within two seconds. The objective function minimizes the total delay of all projects based on their relative importance in the form of weights given as inputs.

Figure 4 shows the number of units supplied (nonrenewable resources) to different projects. Supplier 3 supplies most of the resources in total 315 units, followed by supplier 1, while supplier two supplies the least number of resoruces:206 units. It can also deduce from the figure that for project 1, supplier 1 is the most important; however, for projects 2 and 3, supplier 3 is the most crucial. Figure 4 also shows the amount of nonrenewable resources provided by each supplier. Supplier 2 and Supplier 3 supply zero units of K1, and all the units of K1 are supplied by Supplier 1. Supplier 3 is the only supplier of resource K3 and supplies 114 units of K3 and 201 units of K2, and supplier two only provides 206 units of resource K2. Based on these results, the construction manager can prepare a better collaboration plan with the different suppliers to ensure reliable relationship-building throughout the different projects and avoid delays that might be caused by the lack of flexibility in providing the different resources (e.g., only one supplier selected for K1 and K3)

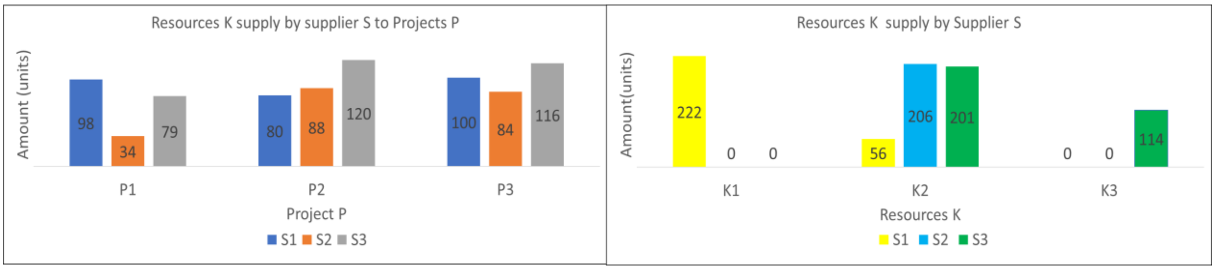

Figure 4: Suppliers "S" Providing Resources Type "K" to Projects "P”

For instance, Figure 5 shows the different suppliers S1, S2, and S3 that have supplied resource types K1, K2, and K3 to different activities of Project 3. The first chart in Figure 5 is for supplier S1, and the second and third charts are for S2 and S3, respectively. For instance, in Figure 5, it can be seen that S1 supplies K1 resources to all activities, S1 supplies K2 resources to some activities: 1, 2, and 8^{th,} and S1 does not supply K3 resources, so there is no grey bar in chart 1 of figure 5. Using the proposed tool, the construction manager can better control the impact of resources on each project's detailed activities and enable efficient management of resources in case of disruptions.

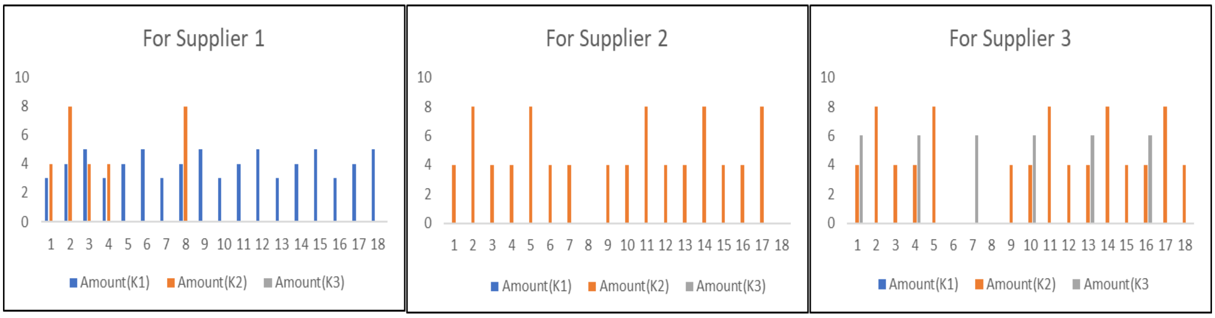

Figure 5: Suppliers Providing Resources K to Activities of Project 3

The model gives the optimal starting time for each activity of each project, and it is shown in Figure 6. Based on the model results, Project 1 should be completed within 12 weeks, Project 2 in 9 weeks, and Project 3 should be completed within 10 weeks. The starting time of activities is also affected because of the difference in precedence relationship among activities of projects.

Figure 6, along with figures 4 and 5, can be utilized collectively to identify the areas to improve decision-making for activities completion time, resources assignment, project idleness, and supplier relationship management.

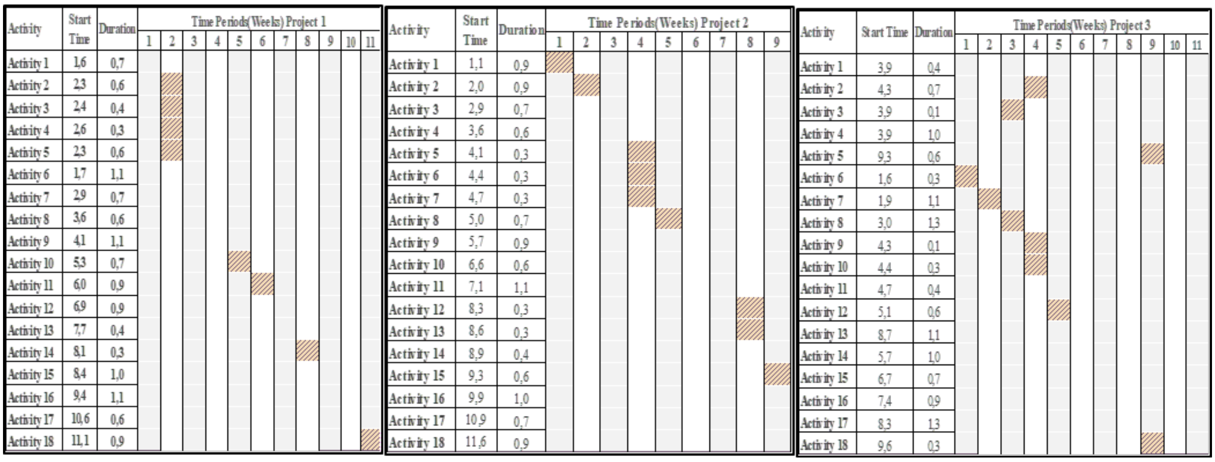

Figure 6: Resultant Gantt Charts of Projects (1,2 & 3)

The completion time and tardiness(delay) of each project are shown in Figure 7. The model can minimize the delay of these projects with respect to the project's due dates. The Project 1 delay is minimized to 2 weeks, the Project 2 delay to a week, and the Project 3 delay to 2.7 weeks. This figure shows the improvement in project time schedules by implementing this model by comparing the before and after conditions.

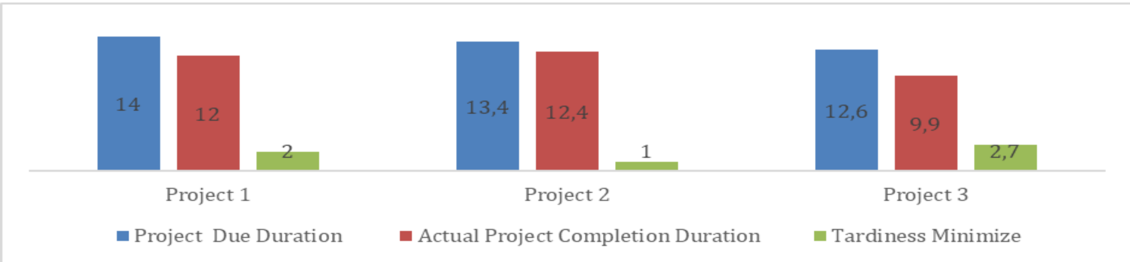

Figure 7: Comparison of Projects Completion Time Before & After Model Implementation (In Weeks)

RESULTS SIGNIFICANCE

The work we proposed here is the interpretation for BPR and logistics optimization to achieve LC. There are many papers available in the literature that provides mathematical optimization solutions for CSC, such as (Zhu, Dai, Liu, Xu, & Alwisy, 2021), (Elmughrabi, Sassi, Dao, & Chabaane, 2020)and (Hsu et al., 2019) but do not provide the way how the mathematical model will be used to achieve LC. By using BPR, we could derive the mathematical model's specifications from reducing waste and facilitating lean practices within CSC (Le & Nguyen, 2021).

Additionally, based on the case study in this paper, the proposed study improves the whole system of a CSC by combining BPM and optimization techniques, which aligns with the goal of lean tools, such as ‘The Last Planner System’ (Daniel, Pasquire, & Ameh, 2014; Le & Nguyen, 2021).

CONCLUSION

This research provides a methodology to minimize the delay (lean) of multiple construction projects simultaneously for the company. This methodology consists of two steps. The first step is related to streamlining the organization's information processes that generate the required inputs for managing and creating schedules. After the generation of these inputs, they are fed to the mathematical mixed integer linear programming model in the second step to give the optimal project schedules and minimize the delay of the projects.

The limitation of this paper is that it only considers nonrenewable resources for projects. Most of the time, real-world projects involve renewable resources such as employees, cranes, and other equipment. Therefore, the addition of these elements to the model will dramatically enhance the capability of the model.

However, this research brings a novel lean methodology that utilizes qualitative and quantitative methods to minimize construction project delays and generate optimal schedules. This will help the project-delivering company manage its resources, project tasks, and suppliers in real-time.

The future steps of this study are to include decisions related to renewable resources in the model and assignment of renewable resources to different activities based on their availability by the model. The decisions related to inventory management can also be included in the model to enhance its capability further.

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SUPPLY CHAIN RISK, DISRUPTION AND RESILIENCE; COMPARISON BY SIZE AND INDUSTRY TYPES

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ABSTRACT

This study categorizes the types of the supply chain (SC) risk events and disruption and characterizes the plans for SC resilience by firm size and by industry in a holistic framework. We applied systematic literature review and analysis of high quality peer-reviewed journal articles published since January 2000. We collected these articles through three main global scientific databases using relevant keywords. The study maps the sources and antecedents of SC risks and disruption in a comprehensive framework for the six SC risk categories of demand, supply, organization, operations, environment, and network/control. Our findings suggest that the SC resilience plans developed by small and medium-sized enterprises (SMEs) are not necessarily the same as those of large enterprises. While collaboration and networking, and risk management are the most crucial resilience capabilities for all firms, applying lean and quality management principles and utilizing information technology are more crucial for SMEs. For large firms, knowledge management and contingency planning are more important. The resilience plans also vary by industry type as well. Based on our analysis, the authors identify theoretical inconsistencies and knowledge gaps in the literature on SC risks and SC resilience, leading to suggested directions for research in this field.

KEYWORDS

Supply chain disruption risk, supply chain resilience, contingency theory, size, industry

INTRODUCTION

Supply chain resilience is increasingly acknowledged as a critical capability to respond, recover, and adapt in the face of severe adversities and disruptions. Most of the research on SC resilience has focused primarily on various antecedents and consequences of SC resilience (Christopher and Peck, 2004; Jüttner, 2005; Blos et al., 2009; Cao and Zhang, 2011; Zhao et al., 2013; Bavarsad et al., 2014; Chen, 2018; Jajja et al., 2018). This research has underplayed two fundamental elements of SC resilience: the firm's size, and the firm's industry. To adapt to SC disruptions, firms have specific processes, organizational structures, and capacities that differ

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by the firms' size and industry; a firm's size and industry have been treated as peripheral factors by most empirical studies and not considered by the systematic literature reviews on SC resilience (e.g., Tukamuhabwa et al., 2015; Ali et al., 2017; Kochan and Nowicki, 2018). The research has typically not provided an in-depth analysis of the impact of firm size and industry type on SC resilience plans, and what has been discovered about the role of firm size and industry remains fragmented. This systematic review analyzes the academic literature to understand SC risk and resilience across different organizational sizes and industries (i.e., manufacturing and service sectors). The service sector includes all service-related businesses and construction. Our literature review and analysis of 224 articles published in a top peer-reviewed journal (at least A-ranked in the journal quality list provided by the Australian Business Deans Council (ABDC) within 2000-2021 - offer an in-depth quantitative and explorative analysis of SC resilience plans that are adopted separately by startups, small and medium-sized enterprises (SMEs), and large enterprises in different industries to mitigate disruptions and ensure business continuity.

Despite the extensive research on SC risk and resilience, understanding how firms' risk management approaches and responses to SC risks and disruptions differ across different firm sizes and industries remains somewhat shallow and fragmented. This systematic literature review analyzes the academic literature to understand SC risk and resilience across different organizational sizes and industries. Our systematic literature review shows that most studies have been conducted without paying enough attention to organizational size and industry. First, our analysis reveals that research on SC risk and resilience for SMEs and startups remains embryonic and needs further development. Second, we find that size is usually considered a control variable in operations and SC management research (Bode et al., 2011; Ambulkar et al., 2015; Bode and Wagner, 2015; Jajja et al., 2018; Azadegan et al., 2019; Parast, 2020). Limiting size and industry only to control variables means the research outcomes cannot easily be extrapolated to different organizational sizes and industries. SMEs and startups usually have capacities, limitations, and priorities that are different from those of large enterprises, emphasizing different practices (Hahn, 2020). For startups, access to funds is the key factor; thus, limited access to funds is a major factor in their SC resilience. For large organizations, access to funds is not critical; process innovation is more important and needs to be emphasized (Golgeci and Ponomarov, 2013; 2015; Parast, 2020). SMEs emphasize agility; large organizations put more emphasis on efficiency (Wieland and Wallenburg, 2013; Thun and Hoenig, 2011).

This paper is organized as follows. We first present the theoretical framework of the study. Section 3 describes the methods used in this study. Section 4 discusses the results; we apply descriptive statistics and analyze the literature using various explorative approaches. Section 5 is the conclusion, including the theoretical and practical implications of this research.

RESEARCH METHODOLOGY

This review focuses only on the structural and systematic analysis of high-quality journal papers from January 2000 to June 2021 using manual screening process, assuming that any prior development in risk analysis would have been considered and updated in the recent papers. The sample was filtered using the inclusion/exclusion criteria shown in Table 1 which were adapted from Liao et al. (2017). This study targeted papers with empirical data or case study analysis. This study excluded conceptual, modeling, and review articles and other types of publications such as theses, books, reports, notes, and news. It is assumed that high-quality research presented in a thesis would have already been published in a high-quality journal.''.

Table 1: Inclusion and exclusion criteria for the systematic literature review

Criteria		Criteria Explanation
Inclusion	Partially related	-The article does not explicitly mention the topic nor uses keywords, but it has the intersection of categories at least in a part/section of the article. - The research efforts of a paper are majorly and deeply dedicated to SC Risk and Resilience.
	Closely related	- The research efforts of the empirical paper are explicitly and specifically dedicated to SC risk and resilience.
Exclusion	Search engine reason	-The article is not written in English, or it was not published in a top peer-reviewed journal (at least A-ranked in the journal quality list provided by the Australian Business Deans Council (ABDC) within 2000-2021.
	Non-related	-The article is not academic (e.g., editorials, newspapers, theses, books, reports, or notes) -the article is a conceptual, modeling, or review article. -The article (topic and keywords) is not related to SC risk and resilience, but to another topic due to homonyms.

According to Podsakoff et al. (2005), papers in high-quality journals can be considered the main source to validate the concepts and impact the subject area. Therefore, this review focuses only on the structural and systematic analysis of high-quality journal papers for the period January 2000 to June 2021, assuming that any prior development on risk analysis would have been considered and updated in the recent papers. This review shows that most of the literature on SC risk and resilience has been developed and published recently. The sample was filtered using the inclusion/exclusion criteria that were adapted from Liao et al. (2017). This study targeted papers with empirical data or case-study analysis. This study excluded conceptual, modeling, and review articles and other types of publications such as theses, books, reports, notes, and news. It is assumed that high-quality research presented in a thesis would have already been published in a high-quality journal. Also, books and reports may have a time lag and are more prescriptive and descriptive; therefore, they are not considered in the review. The focus of the search was limited to ProQuest, ScienceDirect, and Google Scholar databases, as they capture most of the published literature. A correlation between the topic and the journal list mentioned above would help develop a comprehensive list of papers for review.

To search for the relevant literature in the database, publications from leading academic journals were scanned with keywords related to supply chain, risks, disruption, small and medium-sized enterprises, new ventures (startups), agility, and distribution network. Table 2 shows the combination of keywords used in the database search; the approach for selecting these keywords was taken from from Krippendorff (2018). Group A has terms related to resilience as keywords, and Group B has terms related to risk as keywords. Group C has terms related to the combination of resilience, risk, and size of the firm. The keyword search yielded an initial sample of 3,466 publications.

Table 2: Keywords used in the database search

Keywords		
Group A	**Group B**	**Group C**
-Supply chain resilience -Supply resilience -Resilient supply chain -Supply chain resilience distribution networks -Supply chain resilience strategies	-Supply chain risk -Supply risk -Supply chain risk management -Supply chain risk mitigation - Supply chain risk mitigation strategies	-Supply chain risk or resilience - Supply chain and resilience and risk -Supply chain and resilience and risk and SMEs -Supply chain and resilience and risk and large companies - Supply chain and resilience and risk and startups/new ventures

The collected literature was then reviewed for their coverage of supply chain resilience, risk, and disruption domains using Hohenstein et al.'s (2015) definition: "*Supply chain resilience is the supply chain's ability to be prepared for unexpected risk events, responding and recovering quickly to potential disruptions to return to its original situation or grow by moving to a new, more desirable state in order to increase customer service, market share, and financial performance*." This definition captures SC resilience regardless of firm size. Extracting and mapping resilience plans for all firm sizes would help us understand the focus of SC resilience and differences based on company size. For example, startups may have fewer employees and may be more vulnerable to disruptions.

The keyword search yielded an initial sample of 3,466 publications. The collected literature was then reviewed for their coverage of SC resilience, risk, and disruption domains using Hohenstein et al.'s (2015) definition of Supply Chain Resilience. Furthermore, the sample was filtered using the inclusion/exclusion criteria shown in Table 1 which were adapted from Liao et al. (2017). This study targeted papers with empirical data or case study analysis. This study excluded conceptual, modeling, and review articles and other types of publications such as theses, books, reports, notes, and news. From the initial sample of 3,466 publications, 224 (6.5%) publications satisfied all criteria for review. (Appendix A lists the authors of the 224 articles. Appendix B shows the resilience plan themes by firm size. Appendix C shows the frequency of resilience themes.) The theoretical foundations of this study are analyzed on three fundamental approaches: 1) the initial visualization, mapping, and analysis of the literature by size, time, journal, approach, theoretical framework, and variables; 2) exploring, synthesizing, and deeply analyzing the literature, and defining the capacity for resilience; and 3) identifying inconsistencies, gaps, and limitations of the literature and proposing potential research directions to address them.

RESULTS

The results section discusses the differences and similarities of resilience plans developed by startups, SMEs that are not necessarily the same as those of large enterprises, as they usually emphasize different sets of resilience capabilities. Our findings strongly support the value of SC resilience and provide substantial ground for understanding the significant elements of SC resilience across different sizes of firms in different industries. Various aspects of SC resilience have been explored in the literature. The collected literature shows that most of the papers on SC resilience are published in six journals, and only eight journals have published one or more papers from 2016 to 2021. Our data shows that from 2016 to 2021 there is a trend of increased interest in the analysis and assessment of SC resilience and SC risks.

Of the journals in which the 224 reviewed articles were published, 31 journals are identified as A-ranked journals by the Australian Business Deans Council (ABDC). The distribution of risk and resilience articles is highly skewed across journals and does not follow a certain path. About 58% of the publications are published in management journals, and 42% are published in management-related journals.

SUPPLY CHAIN RISKS AND SOURCES

An uncertain event leads to the existence of risk, which can be called a risk event (Manuj and Mentzer, 2008). Our review and analysis of 224 articles confirm that the root causes and antecedents of disruption risk events in an SC can be grouped into demand, supply, organizational, operational, environmental, and network/control risks that may interact; these categories are summarized and explained below. SC resilience is considered in all firm sizes (startups, SMEs, and large enterprises) and many service, construction and manufacturing industries. The service sector includes all service-related businesses and construction.

1. Demand Risks: Demand-related risks are mainly related to the concentration of the customer base, short product life cycles, loss of major accounts, volatility of demand, innovative competitors, forecasting errors, demand fluctuations, risks affecting customers, payment delays, inventory shortages, and technological changes leading to demand changes. Demand-related risks can be addressed through various proactive and reactive policies and solutions such as collaboration, coordination, information and communication technology, and top management support (Manuj and Mentzer, 2008; Christopher and Peck, 2004; Mishra et al., 2021).

2. Supply Risks: Supply risks refer to potential or actual disturbances to the inputs of production of goods or services upstream of the firm. Supply risks include dependence on crucial suppliers, consolidation in supply markets, quality and management issues arising from off-shore sourcing, potential second-tier level disruption, and length and variability of replenishment lead times. Also considered as supply risks are supply chain uncertainties, price and market problems, information asymmetry, and logistics-related issues. Some of the many solutions proposed by researchers are sourcing intermediaries (Vedel and Ellegaard, 2013), integrating external responsiveness and creating dynamic capabilities (Foerstl et al., 2010), and developing effective supplier relationship management (Blackhurst et al., 2011).

3. Organizational Risks: Issues related to the organization are also discussed in the literature. Examples of SC risk events from an organizational perspective are organizational changes, mechanistic systems, employee turnover, employee engagement issues, lack of dedicated resources and training for the SC in the organization, marketing and sales processes, organization finances, and inventory held and managed. Research shows the importance of organizational capability to adopt SC resilience-related measures; the measures could improve flexibility, agility, collaboration (e.g., Jajja et al., 2018; Yang and Hsu, 2018), or integration of digital solutions (e.g., Dubey et al., 2018; Hahn, 2020).

4. Operational Risks: Operational risks are about issues and disruptions in the end-to-end process of producing goods or providing services: receiving inputs; converting inputs to outputs using human resources, physical resources, and non-physical resources; and distributing outputs. The risks include quality-related issues (e.g., defects, errors, discrepancies, reworks, and returns), safety, lengthy set-up times and inflexible processes, manufacturing yield variability, equipment unreliability and breakdowns, limited capacity/bottlenecks, and outsourcing critical business processes. Firms need to be proactive and develop demand forecasting, operation planning, and resource allocation (Zhu et al., 2018).

5. Environmental Risks: Environmental risks include risk events associated with a firm's external environment (natural, political, legal, global, economic, demographic, technological, or socio-cultural) that may directly or indirectly impact the firm's SC networks, marketplace, and ecosystem. This includes natural disasters such as earthquakes, floods, hurricanes, tropical storms, weather changes, and wildfires occurring at any place in the supply chain. Supply chain risks can also be due to the wider level of natural risks such as global pandemics. A few research studies focus on COVID--19-related risks (e.g., Fatemi et al., 2021; El-Baz and Ruel, 2021; Spieske and Birkel, 2021; Pimenta et al., 2022). These papers suggest researching the impact of pandemics on every aspect of supply chains, including inventory management, supplier selection, and SC design.

6. Network/Control Risks: Global supply chains are riskier and more complicated than domestic supply chains because of a variety of links interconnecting a wider network of firms (Manuj and Mentzer, 2008). Ideally, a firm should have an effective awareness system for any potential or actual disturbances to the anticipated flow of product and information from within and between every node or link in its SC networks through which its value stream flows. This might be hard to achieve in practice, but firms should at least strive to familiarize themselves with the details and consequences of these risk events and be more proactive. Every organization has its policies, rules, procedures, and systems that help it govern and control its business affairs and SC-related activities, such as asset management and control, transportation management, and safety stock. Control risk events arise from applying or misapplying these rules and systems (Christopher and Peck, 2004).

QUALITATIVE ANALYSIS

We provide our analysis concerning the two contingency dimensions (firm size and industry segment) examined in the previous sections.

1. Firm size and supply chain resilience

The review provides several important insights related to SC risks and resilience capabilities in startups, SMEs, and large corporations. Because there is only one study related to resilience capability in startups, we provide our assessment for SMEs and large corporations.

We start our evaluation by comparing the common themes in different industry sectors (manufacturing, services and construction) and different sizes (SMEs and large firms). In both groups of the industry size, "collaboration and networking" as well as "risk management" emerge as the most frequently cited resilience capabilities. In summary, in SMEs, collaboration and networking, quality management, risk management, flexibility, information systems/technology, innovation, and supply chain integration are the most highly cited resilience capabilities discussed in the literature in that order. For large corporations, risk management, and collaboration and networking are the most widely cited resilience capabilities, followed by flexibility, contingency planning, information systems/technology, responsiveness, and knowledge management and information sharing in that order. Thus, we see similarities and differences between SMEs and large corporations in terms of resilience capabilities that are emphasized in each group and extracted from the literature. Out of 12 resilience capabilities/ themes listed for both SMEs and large firms, six themes are common between them. However, large organizations tend to be more rigid and hierarchical; they develop action plans and allocate resources for risk management initiatives. SMEs tend to be more organic, agile, and flexible, capitalizing on their organic structure to improve agility, innovation, quality and learning capacities.

2. Industry type and supply chain resilience

Our review of the studies in SC resilience based on the industry type reveals several important insights. First, collaboration-networking and risk management as the most important resilience practices across all industries, followed by a mix of resilience practices such as flexibility, information systems/technology, SC integration, and responsiveness in different orders.

The analysis provides more valuable nuances for developing an industry-specific resilience plan. While flexibility is regarded as an important resilience capability in the chemical industry, information systems are critical to improving resilience in the logistics industry. Agility is an important resilience practice in the manufacturing sector; contingency planning is mostly emphasized in the service industries. Our review suggests that while some general resilience practices are common across industries (e.g., collaboration and networking), the development of resilience capabilities should be based on the nature of the industry.

Regarding resilience capabilities, further analysis suggests a clear distinction between manufacturing industries and service industries. While collaboration and networking as well as risk management are important for both sectors, the manufacturing sector places more emphasis on flexibility and SC integration, and the service sector places more emphasis on knowledge management, information systems/technology, and responsiveness. For manufacturing firms, slack resources are highlighted as a resilience-enhancing capability; for service firms, there is not much discussion on the effectiveness of this capability.

3. Firm size and industry type combination

We previously examined the effect of firm size and type of industry on the development of resilience capabilities separately. It would be insightful for organizations to realize what type of resilience capabilities should be developed based on the overall impacts of these two dimensions of firm size and industry together. This requires a more detailed assessment of the literature to assess the combination of both contingency factors (firm size - industry).

To properly address the combination of size - industry, we identified SC resilience studies that clearly focused on firm size and industry type. We only reviewed articles where these two dimensions were clearly identified. Thus, we excluded studies that used a cross-sectional approach or studies in which firm size was a mix of large and SMEs or not specified. Using this procedure, we identified 96 articles that met our criteria. Table 3 below shows our practical assessment of the size-industry combination. We evaluated the articles based on two dimensions of size (i.e., large and SME) and two dimensions of industry (i.e., manufacturing and service).

Quadrant 1: Large Firms - Manufacturing: The most widely cited resilience practices for large manufacturing firms are risk management plans, collaboration and networking, and knowledge management. The development of resilience capability in large manufacturing firms entails the development of a risk management plan, which includes identifying, assessing, avoiding, mitigating, transferring, sharing, and accepting risk; this encompasses all activities of risk management. Overall, the literature suggests that large manufacturing firms are more involved in risk management plans than their service counterparts.

Quadrant 2: Large Firms – Services: The overall resilience capability practices for large service firms are collaboration and networking, risk management plans, and contingency planning. Large service organizations seem to have a much narrower focus on risk management practices: which consist of identifying steps to be taken if a disruption risk occurs (contingency planning). Such a distinction between risk management and contingency plans may suggest that large manufacturing organizations are exposed to more disruption risks.

Quadrant 3: SMEs - Manufacturing: Our review of the studies in this domain identified collaboration and networking, flexibility, and quality management (i.e., lean, and continuous improvement) as the main resilience capabilities of SMEs in the manufacturing space. The literature suggests that the more resilient manufacturing SMEs require assistance from sources other than banks and government loans and grants. They need to rely on collaborating firms such as large corporations and international financial institutions (Moore and Manring, 2009; Gunasekaran et al., 2011; Pal et al., 2014; Santoro et al., 2020). In addition, manufacturing SMEs should be more organic and flexible and use a significant number of external linkages that can help them become more resilient and more successful at the same time. Applying quality management practices, such as lean and continuous improvement approaches are highly recommended by the literature (Demmer et al., 2011; Pal et al., 2014) and they can help SMEs to be more effective and efficient, innovative and responsive to any changes and disruptions.

Quadrant 4: SMEs – Services: Our review of the studies in this domain identified risk management, information systems/technology, and collaboration and networking as the main resilience capabilities for service SMEs. Collaboration and networking capabilities have the same significance for service SMEs as they have for manufacturing SMEs. To establish resilience at the firm level and the supply chain level, SMEs must incorporate information systems and advanced IT infrastructure for effectively informed decision-making, information sharing, communication and organizational learning (Jayaram et al., 2014; Ali et al., 2017).

Table 3: Resilience capabilities for different size-industry configurations (by priority order)

Industry/Size	Large	SME
Manufacturing	- Risk management - Collaboration & networking - Knowledge management	- Collaboration & networking - Flexibility - Quality Management (lean, continuous improvement)
Service (and Construction)	- Collaboration & networking - Risk management - Contingency planning	- Risk management - Information systems/technology - Collaboration & networking

Table 3 summarizes the resilience capabilities based on the size and industry type. Since there was only one study related to resilience capabilities in startups, we cannot provide a discussion on resilience capabilities in the startup domain. The single study conducted in the startup space discussed the importance of data analytics and the platform economy (i.e., information systems/technology for digital business platforms) for improving SC operational efficiency and productivity (Hahn, 2020).

CONCLUSIONS AND IMPLICATIONS

Our attempt was to answer the research question of "How are SC risk and resilience applied and manifested across different organizational sizes and industries?". The review of 224 articles shows that most SC risk and resilience studies have been conducted without paying enough attention to organizational size and industry. Both the size and the industry of firms are considered control variables in these studies. However, SMEs and startups usually have different capacities, limitations, and priorities from those of larger enterprises. Firms in different industries operate amid different realities and face different internal and external factors when devising their resilience plans and achieving SC resilience. Thus, firm size and industry are likely to have a profound influence on how SC risk and resilience are applied and manifested among organizations.

THEORETICAL IMPLICATIONS

This study contributes to the literature on SC risk and resilience in several ways. First, the study builds upon the relatively dispersed previous research into SC risk and resilience, and it maps the sources and antecedents of SC risks and disruption in a comprehensive framework of six categories of risk events: demand, supply, organization, operations, environment, and network/control.

Second, to the best of our knowledge, this study is the first theoretical assessment for startups, SMEs, and large organizations for understanding the SC risks and disruptions that may be caused by due to various factors discussed above. Our findings suggest that the SC resilience plans for startups and SMEs are not necessarily the same as those for large organizations. While risk management and SC resilience plans require allocating resources and developing an effective action plan, startups and SMEs usually suffer from a lack of sufficient resources. However, larger enterprises can better overcome SC risks and be more resilient. According to our literature review, there is only one study for startups: Hahn (2020) highlighted the importance of data analytics, information systems, and the platform economy (digital platform) for SC resilience in startups. For SMEs, in addition to information systems, collaboration and networking, quality management, risk management and flexibility are more important. Besides collaboration and networking, larger enterprises' risk management, flexibility, contingency planning, and information systems/technology are the most important capabilities for their SC resilience plans.

Our analysis highlighted the SC resilience differences by both size and industry type. According to our result (Table 3), collaboration and networking are the most crucial resilience capabilities for all firms. Firms can be more competitive in the market and more resilient by benefiting from the synergetic effects of collaborative relationships with their SC partners (Ali et al., 2017). These are some of the key suggestions: collaboration with customers (Liu and Lee, 2018); strategic collaborative learning (Hallikas et al., 2005); collaborative efforts to align information and find substitutive parts (Messina et al., 2020); and integrating both configuration and manufacturing flexibilities for better alliances with both new and current SC partners (Huang and Lu, 2020). According to our study, risk management is an effective and popular approach for large firms to be more resilient because of their capabilities and resources for risk management compared with startups and SMEs that face resource and skill shortages. As highlighted by various studies, firms need to be proactive and conduct an SC risk assessment and devise mitigation strategies before facing disruptions (e.g., Thun and Hoenig, 2011; Grötsch et al., 2013; Swierczek, 2016; Rezapour et al., 2017).

Another effective part of a SC resilience plan among large manufacturing enterprises is knowledge management: collecting, managing, and sharing SC knowledge, expertise, and information in organizations. Many SC scholars highlight it as an effective part of a resilience plan (e.g., Hendricks and Singhal, 2005; Essuman et al., 2020; Mishra et al., 2021). Continuity and contingency planning are also effective and most frequently appear in resilience plans for large service organizations that are highlighted in the literature (e.g., Norrman and Jansson, 2004; Davarzani et al., 2015; Lam and Bai, 2016; Islam et al., 2021).

For SMEs, in addition to collaboration and networking, flexibility (i.e., flexibility of operations, changing suppliers, rerouting and alternative shipping paths/methods, input substitutes, design flexibility, manufacturing flexibility, and flexibility in organizational structure) is the most important resilience solution in SME manufacturing sectors (e.g., Pal et al., 2014; Stranieri et al., 2017; Bode and Macdonald, 2017). This is followed by applying lean and other quality management solutions for the manufacturing SMEs (e.g., Demmer et al., 2011; Govindan et al., 2014; Pal et al., 2014). At its core, lean theory identifies eight types of waste, also known as "muda" in Japanese, which are defects, overproduction, waiting, non-utilized talent, transportation, inventory, motion, and excess processing (Liker, 2004). We all know that by applying lean principles to supply chain management, organizations can identify and eliminate waste in all aspects of the supply chain, from procurement and inventory management to production and delivery. This can lead to a more efficient and responsive supply chain, with reduced lead times, lower costs, and improved customer satisfaction. For SMEs in the service sector, in addition to applying effective risk management systems, information systems/technology, and effective collaboration and networking (e.g., Hahn, 2020; Belhadi et al., 2021) are important resilience solutions in that order.

PRACTICAL IMPLICATIONS

This study has some effective practical implications as well. First, SMEs and large organizations should become familiar with the main causes and antecedents of their SC risk events and improve their SC resilience by developing effective *ex-ante* and *ex-post* plans for dealing with disruptions. In addition to responsive efforts to minimize the impacts of disruptions, firms need to be proactive by implementing preventive measures to mitigate SC risks and become more resilient. Second, firms should recognize that their SC resilience plans are not necessarily the same for different industry sectors. Risk management, collaboration, networking, and knowledge management (in that order) are the most important resilience plans/themes in large manufacturing firms. Nonetheless, collaboration and networking, risk management, and contingency plans (in that order) are the most effective resilience plans/themes for large service firms. Both manufacturing firms and service firms need to focus on effective collaboration and networking with their partners and key stakeholders, to mitigate the negative impact of SC disruptions.

Third, manufacturing operations place more importance on identifying, assessing, avoiding, mitigating, transferring, and sharing plans for risk events (i.e., risk management), quality management, and knowledge development and sharing. Manufacturing operations that are less flexible than service operations, which mainly focus on business continuity plans and effective information systems. The nature of manufacturing operations is different from the nature of service operations: manufacturing is a functional, mechanistic, production-oriented model; services are more organic, humanistic, and relationship-based models (Duncan and Moriarty, 1998; Truong and Hara, 2018). Therefore, we expect manufacturers to focus more on risk management and preventive measures compared to service organizations, which mainly focus on the steps to be taken if disruptions occur (contingency planning).

Fourth, business managers need to be aware of the types of SC risk events if they implement preventive measures or responses for those risk events. The likelihood of occurrence of those risk events, the consequences of the occurrence of those risk events, and effective *ex-ante* and *ex-post* resilience plans will vary with the firm size and firm industry. We have listed resilience plans/themes (prioritized by firm size) that businesses can consider in Appendix B.

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